Acquisition of non-adjacent phonological dependencies : From speech perception to lexical acquisition

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Acquisition de relations phonologiques non-adjacentes : de la perception de la parole à l'acquisition lexicale

Présentée par
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Sous la direction de
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Soutenue le 1^{ere} août 2012

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UNIVERSITE PARIS DESCARTES

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Resumé

Les langues ont de nombreux types de dépendances, certaines concernant des éléments adjacents et d'autres concernant des éléments non adjacents. Au cours des dernières décennies, de nombreuses études ont montré comment les capacités précoces générales des enfants pour traiter le langage se transforment en capacités spécialisées pour la langue qu'ils acquièrent. Ces études ont montré que pendant la deuxième moitié de leur première année de vie, les enfants deviennent sensibles aux propriétés prosodiques, phonétiques et phonotactiques de leur langue maternelle concernant les éléments adjacents. Cependant, aucune étude n'avait mis en évidence la sensibilité des enfants à des dépendances phonologiques non-adjacentes, qui sont un élément clé dans les langues humaines. Par conséquent, la présente thèse a examiné si les enfants sont capables de détecter, d'apprendre et d'utiliser des dépendances phonotactiques non-adjacentes. Le biais Labial-Coronal, correspondant à la prévalence des structures commençant par une consonne labiale suivie d'une consonne coronale (LC, comme **b**a**t**eau), par rapport au pattern inverse Coronal-Labial (CL, comme **t**a**b**ac), a été utilisé pour explorer la sensibilité des nourrissons aux dépendances phonologiques non-adjacentes. Nos résultats établissent qu'à 10 mois les enfants de familles francophones sont sensibles aux dépendances phonologiques non-adjacentes (partie expérimentale 1.1). De plus, nous avons exploré le niveau auquel s'effectuent ces acquisitions. En effet, des analyses de fréquence sur le lexique du français ont montré que le biais LC est clairement présent pour les séquences de plosives et de nasales, mais pas pour les fricatives. Les résultats d'une série d'expériences suggèrent que le pattern de préférences des enfants n'est pas guidé par l'ensemble des fréquences cumulées dans le lexique, ou des fréquences de paires individuelles, mais par des classes de consonnes définies par le mode d'articulation (partie expérimentale 1.2). En outre, nous avons cherché à savoir si l'émergence du biais LC était liés à des contraintes de type maturationnel ou bien par l'exposition à l'input linguistique. Pour cela, nous avons tout d'abord testé l'émergence du biais LC dans une population présentant des différences de maturation, à savoir des enfants nés prématurément (± 3 mois avant terme), puis comparé leurs performances à un groupe d'enfants nés à terme appariés en âge de maturation, et à un groupe de nourrissons nés à terme appariés en âge chronologique. Nos résultats indiquent qu'à 10 mois les enfants prématurés ont un pattern qui ressemble plus au pattern des enfants nés à terme âgés de 10 mois (même âge d'écoute) qu'à celui des enfants nés à terme âgés de 7 mois (même âge de maturation ; partie expérimentale 1.3). Deuxièmement, nous avons testé une population apprenant une langue où le biais LC n'est pas aussi clairement présent dans le lexique : le japonais. Les résultats de cette série d'expériences n'a montré aucune préférence pour les structures LC ou CL chez les enfants japonais (partie expérimentale 1.4). Pris ensemble, ces résultats suggèrent que le biais LC peut être attribué à l'exposition à l'input linguistique et pas seulement à des contraintes maturationnelles. Enfin, nous avons exploré si, et quand, les acquisitions phonologiques apprises au cours de la première année de la vie influencent le début du développement lexical au niveau de la segmentation et de l'apprentissage des mots. Nos résultats montrent que les mots avec la structure phonotactique LC, plus fréquente, sont segmentés (partie expérimentale 2.1) et appris (partie expérimentale 2.2) à un âge plus précoce que les mots avec la structure phonotactique CL moins fréquente. Ces résultats suggèrent que les connaissances phonotactiques préalablement acquises peuvent influencer l'acquisition lexicale, même quand il s'agit d'une dépendance non-adjacente.

Abstract

Languages instantiate many different kinds of dependencies, some holding between adjacent elements and others holding between non-adjacent elements. During the past decades, many studies have shown how infant initial language-general abilities change into abilities that are attuned to the language they are acquiring. These studies have shown that during the second half of their first year of life, infants became sensitive to the prosodic, phonetic and phonotactic properties of their mother tongue holding between adjacent elements. However, at the present time, no study has established sensitivity to nonadjacent phonological dependencies, which are a key feature in human languages. Therefore, the present dissertation investigates whether infants are able to detect, learn and use non-adjacent phonotactic dependencies. The Labial-Coronal bias, corresponding to the prevalence of structures starting with a labial consonant followed by a coronal consonant (LC, i.e. **b**a**t**), over the opposite pattern (CL, i.e. **t**a**b**) was used to explore infants sensitivity to non-adjacent phonological dependencies. Our results establish that by 10 months of age French-learning infants are sensitive to non-adjacent phonological dependencies (experimental part 1.1). In addition, we explored the level of generalization of these acquisitions. Frequency analyses on the French lexicon showed that the LC bias is clearly present for plosive and nasal sequences but not for fricatives. The results of a series of experiments suggest that infants preference patterns are not guided by overall cumulative frequencies in the lexicon, or frequencies of individual pairs, but by consonant classes defined by manner of articulation (experimental part 1.2). Furthermore, we explored whether the LC bias was trigger by maturational constrains or by the exposure to the input. To do so, we tested the emergence of the LC bias firstly in a population having maturational differences, that is infants born prematurely (± 3 months before term) and compared their performance to a group of full-term infants matched in maturational age, and a group of full-term infants matched in chronological age. Our results indicate that the preterm 10-month-old pattern resembles much more that of the full-term 10-month-olds (same listening age) than that of the full-term 7-month-olds (same maturational age; experimental part 1.3). Secondly we tested a population learning a language with no LC bias in its lexicon, that is Japanese-learning infants. The results of these set of experiments failed to show any preference for either LC or CL structures in Japanese-learning infants (experimental part 1.4). Taken together these results suggest that the LC bias is triggered by the exposure to the linguistic input and not only to maturational constrains. Finally, we explored whether, and if so when, phonological acquisitions during the first year of life constrain early lexical development at the level of word segmentation and word learning. Our results show that words with frequent phonotactic structures are segmented (experimental part 2.1) and learned (experimental part 2.2) at an earlier age than words with a less frequent phonotactic structure. These results suggest that prior phonotactic knowledge can constrain later lexical acquisition even when it involves a non-adjacent dependency.

Contents

List of papers presented in this dissertation

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Introduction

“Language is the blood of the soul
into which thoughts run and out of which they grow.”
Oliver Wendell Holmes

The human language involves different sound combinations associated with arbitrary referents, organized according to a complex grammatical structure, which allows the production of an infinite number of sentences. This incredible human ability opens all kinds of possibilities, like being able to argue, discuss, debate, chat, think, bargain, negotiate, declare, question, joke, order, gossip, tell stories, express emotions, share information… about the past, the present or the future. No other species on earth is equipped with such an extraordinary capacity; in terms of Miller (1983), we are all “*informavores*” immersed in a communicating world. But, how are infants able to learn such a complex system?

This dissertation explores infants’ language acquisition abilities, focusing on their capacity to learn the non-adjacent sound combinations that occur in their native language. In other words we explore infants’ ability to acquire some of the phonotactic regularities of the language. This intellectual journey starts exploring speech perception in the first year and ends exploring lexical acquisition in the second year. Prior to the presentation of our experimental work, we present a review of the literature on language acquisition.

Before infants are able to understand a word or a sentence, they have to deal with a huge amount of information in order to learn the properties of their native language. Since the second half of the 20th century, a lot of research has focused on exploring infants’ ability to learn a language. Some of these studies have shown that many changes take place during the first months of life, concerning the way infants process speech sounds.

Furthermore, the kinds of changes that appear during this period seem to be specifically linked to the linguistic input to which infants are exposed, hence their importance in relation to language acquisition. Indeed, during the past decades many studies have been conducted to determine on one side which discrimination capacities are innate and on the other side how these general capacities change with exposure to the linguistic input. Thus, researchers are interested in the interaction between the general basic capacities belonging to the auditory perceptive system (nature) and the process of learning a specific language through speech exposure (nurture).

The fact that infants acquire language so rapidly and almost effortlessly has suggested the existence of different prewired mechanisms and perceptual capacities underlying speech processing. This human predisposition to learn language has been conceptualized in different ways, such as *the language acquisition device* (LAD; Chomsky, 1965), *the language making capacity* (LMC; Slobin, 1973; 1985), *the language procedures* (Pinker, 1984), the *operating principles* (MacWhinney, 1985; Slobin, 1973; 1985), the *perceptual or memory primitives* (POMPs; Endress, Nespor, & Mehler, 2009)… The general idea behind all these concepts is similar: language learning is guided by a body of perceptual capacities and a set of early general mechanisms preexisting linguistic exposure. In other terms, language acquisition would be part of an "*innately guided learning*" process (Gould & Marler, 1987; Jusczyk & Bertoncini, 1988; Jusczyk, 1997; Marler, 1991), allowing infants to select all the relevant information that is necessary to develop all their linguistic capacities.

In this perspective, different studies have shown the existence of specific patterns or structures that are automatically detected and processed right after birth, as a result of the way in which the early perceptual system operates and is organized. Some examples of these perceptual primitives are detectors of edges (Henson, 1998; Endress, et al., 2009; Endress & Mehler, 2009; Endress, Scholl, & Mehler, 2005; Peña, Bonatti, Nespor, & Mehler, 2002), identity relations (Endress, Nespor, & Mehler, 2009; Gomez, Gerken, & Schvaneveldt, 2000; Endress, Dehaene-Lambertz, & Mehler, 2007; Tunney & Altmann, 2001; Gervain, Macagno, Cogoi, Peña, & Mehler, 2008), and all the early speech discrimination capacities (Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Bertoncini, et al., 1987, 1988; Cheour-Luhtanen et al., 1995; Groome, et al., 1997a; Lecanuet, et al., 1987; 1989; Nazzi, et al., 1998...).

In addition, there is an increasing amount of evidence showing the existence of a general ability to automatically compute distributional regularities in the input. This capacity has been found in infants from 2 months of age (Saffran, Aslin, & Newport, 1996; Gomez & Gerken, 1999; Kirkham, Slemmer, & Johnson, 2002…), adults (Cleeremans, 1993; Saffran, Newport, & Aslin, 1996; Saffran, Johnson, Aslin, & Newport, 1999; Pacton, Perruchet, Fayol, & Cleeremans, 2001; Fiser & Aslin, 2002; Creel, Newport, & Aslin, 2004…) and to a certain degree in non-human primates (Greenfield, 1991; Savage-Rumbaugh et al., 1993; Hauser, Newport, & Aslin, 2001; Fitch & Hauser, 2004). This general capacity is assumed to be very useful in language acquisition, facilitating the discovery of linguistic regularities. Saffran, Aslin and Newport (1996) found the impressive result that 8-month-old infants are able to segment trisyllabic words from a continuous speech stream of an artificial language, to which they have been familiarized for only 2 minutes. Infants were able to do so based on the transitional probabilities between the syllables of that language (more details of this study will be given subsequently). Therefore, this study establishes infants' ability to compute complex statistics in the speech input to find language regularities. Furthermore very early in life infants have been shown not only to be able to extract regularities, but to make generalizations on the basis of these regularities (Gervain, Macagno, Cogoi, Peña, & Mehler, 2008; Marcus, Vijayan, Bandi Rao, & Vishton, 1999; Gomez & Gerken, 1999). The ability to extract rules is a key feature in language acquisition, since learners do not only memorize sequences, but they rather learn generalizable rules allowing them to produce an infinite number of structures from a finite number of elements.

To summarize, there is evidence suggesting the existence of various prewired general mechanisms and perceptual capacities that underlie language acquisition. All these prewired abilities equip infants with a sort of “tool box” (as suggested by Endress, Nespor, & Mehler, 2009) containing the necessary devices to perceive, analyze, store, use, interpret and produce sound sequences to communicate with others, and it is through exposure to the linguistic input that infants can use all these tools to acquire the relevant properties of their native language. The next section will be dedicated to trace this early linguistic development.

Early speech perception

Many studies have shown that during the second half of the first year of life many changes occur in infants' initial speech perception abilities. More importantly, the kinds of changes that happen in this period seem to be specifically linked to the input to which infants are exposed. In this section, we review the literature on this topic, underlying the kinds of changes that occur during this period at the segmental and suprasegmental levels.

Prosodic information

Prosody makes reference to the suprasegmental properties of language, including stress, rhythm and intonation of speech. Developmental research at this level investigates whether or not, and if when, infants react to differences in tones, stress patterns, rhythms and other prosodic dimensions.

Initial abilities

Many studies have shown that sensitivity to prosodic properties can be found very early in life, even before birth. Different studies have shown that near-term fetuses are able to distinguish low from high musical notes (Lecanuet, Granier-Deferre, Jacquet, & DeCasper, 2000), and a female from a male voice (Lecanuet, Granier-Deferre, Jacquet, & Busnel, 1992). Both discriminations are made on the basis of prosodic cues that are already perceived in utero.

Furthermore, studies about language rhythm discrimination showed that newborns are able to distinguish sentences drawn from different languages on the basis of prosodic cues (Mehler, et al., 1988; Nazzi, Bertoncini, & Mehler, 1998). Using the non-nutritive sucking method, Mehler et al. (1988) showed that French newborns are able to discriminate French sentences from Russian ones, while American 2-month-olds can differentiate English sentences from Italian sentences. However neither the French nor the American group was able to distinguish two completely unfamiliar languages. Based on these results, Mehler et al. (1988) concluded that infants need to be familiar to at least one of the languages to discriminate them. However, a decade later, Nazzi et al. (1998) observed that French newborns can distinguish stress-timed English from mora-timed Japanese, but not stress-timed English from stress-timed Dutch (Nazzi, et al., 1998). These results showed firstly, that discrimination is possible even when languages were not familiar to infants. Secondly, they established that these discriminations are based on the rhythmic properties of speech, infants being able to distinguish two languages belonging to different rhythmic classes, but not two languages from the same rhythmic class.

In addition, newborns have also been shown to be sensitive to stress properties at the lexical level (Sansavini, Bertoncini, & Giovanelli, 1997; van Ooijen, Bertoncini, Sansavini, & Mehler, 1997). Using the high-amplitude sucking procedure, Sansavini et al. (1997) found that Italian newborns are able to discriminate different stress patterns presented in different contexts (disyllabic unvaried words /‘mama/ versus /ma’ma/, trisyllabic varied words /‘tacala/ versus /ta’cala/, or multiple disyllabic varied words /’gaba/ /’nata/ /’lama/… versus /ga’ba/ /na’ta/ /la’ma/…). Similarly, van Ooijen et al. (1997) found that French newborns are sensitive to stress differences in English words, distinguishing between weak-strong disyllabic words (i.e. belief, control…) and strong monosyllabic words (i.e. nose, dream…). Likewise, Nazzi, Floccia, and Bertoncini (1998) have shown that French newborns are sensitive to the pitch contour characteristics of Japanese words (Low-High versus High-Low). Taken together, these results show that fetuses and newborns are sensitive to the suprasegmental properties of the language such a as rhythm, pitch and stress at both the sentence and word levels.

Early changes

On the one hand, studies focusing on language discrimination have shown that under some circumstances, 5-month-old infants are able to distinguish two languages belonging to the same rhythmic class (Nazzi, Jusczyk, & Johnson, 2000). Nazzi et al. (2000) showed that at 5 months English-learning infants continue to be able to discriminate pairs of languages belonging to different rhythmic classes (i.e. British English versus Japanese). More importantly, they found that infants can also discriminate languages within a rhythmic class, when their native language (or one of its variants) is included (i.e. American versus British English or British English versus

Dutch). Similar results were found in monolingual and bilingual Catalan- and Spanish-learning infants who were also able to distinguish two languages (Catalan and Spanish) between and whithin rhythmic classes at 4 months (Bosch & Sebastián-Gallés, 1997; 2001).

On the other hand, different studies have suggested acquisitions of native language properties at the word level. Using the HPP method (Head-turn Preference Procedure), Jusczyk, Friederici, Wessels, Svenkerud, and Jusczyk (1993b) observed that 6-month-old English infants were able to distinguish English words from Norwegian words by means of differences at the prosodic level.

Moreover, another experiment found that between 6 and 9 months English infants develop a preference for the trochaic stress pattern that is more frequent in English (Jusczyk, et al., 1993a). Similarly, German infants develop such preference between 4 and 6 months of age (Höhle, Bijeljac-Babic, Herold, Weissenborn, & Nazzi, 2009). Höhle et al. (2009) suggested that the timing differences observed between English and German infants were possibly triggered by methodological differences, as the prosodic variations in the German stimuli might have been perceptually more salient than the ones in the English stimuli, given that the Jusczyk et al. (1993a) stimuli contained high phonetic variability (different trochaic and iambic words), while the Höhle et al. (2009) stimuli had low phonetic variability (multiple trochaic and iambic tokens of a single pseudo-word). Furthermore, Höhle et al. (2009) found no preference in 6-month-old French infants, confirming that the emergence of the trochaic bias is language-specific. This negative result was predicted by Nazzi et al. (2006), given the rhythmic properties of French, that has been described as a language without lexical accent, characterized by a lengthening of phrases rather than an iambic stress. In the same vein, Skoruppa et al. (2009) have shown language-specific changes in early stress perception. They found that at 9 months, infants learning Spanish, a language with lexical contrastive stress, are able to discriminate multiple trochaic from multiple iambic words, even when they show no preference for any of these patterns (Pons & Bosch, 2007). In contrast, 9-month-old French-learning infants were only able to discriminate the stress patterns when the stimuli contained low phonetic variability, that is, only when multiple tokens of a single pseudo-word were presented. The authors concluded that even if at 9 months French infants are able to perceive the acoustic correlates of stress, they are unable to process stress at a phonological level, given the rhythmic properties of French (Skoruppa, et al., 2009). These results are in line with those of a subsequent experiment showing that 8- and 12-month-old English-learning infants are sensitive to lexical stress pattern information present in their native language (Skoruppa, Cristià, Peperkamp, & Seidl, 2011).

Additionally, different studies have also shown language-specific changes, occurring during the first year of life, affecting the capacity to discriminate lexical tone contrasts (Mattock & Burnham, 2006; Mattok, Molnar, Polka, & Burnham, 2008). Mattock and Burnham (2006) tested infants' capacity to discriminate lexical tones and non-speech tone analogs (violin sound) in two groups of infants, learning either English (a language without lexical tone) or Chinese (a language with lexical tone). They found that at 6 months both English and Chinese infants were able to distinguish speech and non-speech tones. The same pattern was observed at 9 months for the Chinese group. However, at 9 months, English-learning infants were no longer able to discriminate the lexical tones, although they still discriminated the non-speech analogs. This decrease in lexical tone discrimination was also observed in French-learning infants (Mattok, et al., 2008). Taken together, these results establish that during the second half of the first year of life, there is a decrease in the capacity to discriminate non-native contrasts, which is linked to the acquisition of the prosodic properties of the native language.

Phonetic information

At the segmental level, research is interested in studying how infants perceive, decode and acquire the categories of speech sounds. On the one hand, studies explore the existence of innate discrimination capacities of phonetic contrasts, that would not be limited to the sounds present in their speech environment. On the other hand, they explore how, during the first year of life, infants start specializing in the contrasts that are used in their native language, learning native language phonetic categories, and at the same time how they start having difficulties to perceive non-native contrasts, just like adults do.

Initial capacities

To explore these questions, researchers have first studied how very young infants perceive, represent and discriminate basic speech sounds. Eimas, Siqueland, Jusczyk, and Vigorito (1971) tested the phonetic discrimination capacities of 1- and 4-month-old infants, using a non-nutritive sucking paradigm. They wanted to know if infants from English-speaking families were able to distinguish the consonantal voicing contrast that distinguishes the syllables /ba/ and /pa/. Their results showed that infants were able to distinguish /ba/ from /pa/. Moreover, they were not able to distinguish between two acoustically different exemplars of /ba/ or two different exemplars of /pa/, suggesting the existence of categorical perception for consonants, as found in adults. Many studies then explored different contrasts other than voicing, showing that young infants are able to distinguish a contrast based on place of articulation (i.e. ba vs. ga), a plosive consonant versus a semi-vowel (i.e. ba vs. wa), semi-vowels (i.e. wa vs. ya), oral versus nasal consonants (i.e. ba vs. na), two nasal consonants (i.e. na vs. ma) or two liquid consonants (i.e. ra vs. la; c.f. Jusczyk, 1997). Some of these phonetic discrimination capacities have been demonstrated even in newborns (Bertoncini, Bijeljac-Babic, Blumstein, & Mehler, 1987).

Concerning vocalic contrasts, Trehub (1973) showed that 1- to 4-month-old infants are able to distinguish between the cardinal vowels /a/, /i/, and /u/. Some years later, authors like Bertoncini et al. (1987, 1988) and Cheour-Luhtanen et al. (1995) revealed that the ability to discriminate vowels is already present at birth. Furthermore, different studies showed that near-term fetuses can discriminate /a/ from /i/ embedded in different contexts (/a/ vs. /i/, /ba/ vs. /bi/, /babi/ vs. /biba/; Groome, Mooney, Holland, Bentz, & Atterbury, 1997a; Groome et al., 1997b; Lecanuet, et al., 1987; 1989; Shahidullah & Hepper, 1994). Additionally, Kuhl (1983) showed that under some circumstances infants are even able to differentiate some vowels that are acoustically closer, such as /a/ and /o/. All these results show that there are phonetic discrimination capacities available very early in life.

Early changes

A great number of studies have focused on the process by which infants learn the phonetic properties of their native language (Werker & Tees, 1984; Kuhl, 1991; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Best, McRoberts & Sithole, 1988; Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995). In this perspective, Werker and Tees (1984) tested English-learning infants’ ability to discriminate two non-native contrasts, one from Hindi (/ṯa/ vs /ta/), and one from Salish (/k’i/ vs /q’i/) at three different ages (6-8, 8-10, and 10-12). They found that 6-to-8-month-olds could distinguish both non-native contrasts. However, the results of the 8-to-10-month-olds showed a decrease in the capacity to discriminate these phonetic contrasts, while no evidence of discrimination was found in the 10-to-12-month-olds. In contrast, 10-to-12-month-old Hindi- and Salish-learning infants were able to discriminate their native contrasts respectively (Werker & Tees, 1984). Similar results were found by Kuhl et al. (2006) testing English and Japanese infants with a contrast present in English but not in Japanese (/ra/ vs /la/). However, as shown by Best and colleagues (Best, et al., 1988; Best, 1991), not all non-native contrasts stop being discriminated at the end of the first year of life: some contrasts, falling in areas of the phonetic space in which no native phonemes are present, can remain discriminable even in adulthood. These patterns of results have been confirmed by different electrophysiological studies (Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2005; Kuhl et al., 2008) further showing that processing of native contrasts changes and probably becomes more efficient over development.

Similar early perceptual changes have also been found for vowel discrimination (Polka & Werker, 1994; Kuhl, 1991; Kuhl et al., 1992). Accordingly, Polka and Werker (1994) found a decrease in English-learning infants’ discrimination of German vocalic contrasts. Similarly, 6-month-old English- and Swedish-learning infants exhibit a language-specific pattern of vocalic phonetic perception. These results suggest that by 6 months of age, infants already have prototype representations of the vowels present in their native language, allowing them to determine phonemic categories.

Moreover, Anderson, Morgan, and White (2003) suggested that relative frequency of sound sequences plays an important role in phonological development. According to Anderson and colleagues, infants will acquire frequent phonetic categories earlier than less frequent ones, and consequently the discrimination performance of non-native contrasts will decline earlier for frequent phonetic categories. To test their hypothesis, English-learning 6.5- and 8.5-month-olds were tested on their discrimination of two non-native contrasts, one involving a phonetic category that is very frequent in English (coronals) and the second one involving a less frequent phonetic category (dorsals). Their results showed that while 6.5-month-olds are able to discriminate both kinds of contrasts, 8.5-month-olds already show a decline in their ability to discriminate non-native coronal contrasts while they continue to discriminate non-native dorsal ones. Therefore, between 6.5 and 8.5 months, infants start acquiring the frequent consonantal categories of their language, namely coronals.

Taken together, the above results establish the existence of early developmental changes regarding the way infants perceive speech sounds. During the second half of their first year of life, infants become attuned to the properties of their native language, allowing the emergence of language-specific phonemic representations, and better processing of native contrasts. In addition, this specialization in the processing of native contrasts has been shown to go together with a decrease in the discrimination of some non-native contrasts.

However, even if knowledge about the specific phonetic categories of a given language is crucial in language acquisition, it is not all there is to discover about the sound structure of a language. Infants also need to learn the organization of these sounds, in other words, the patterns and restrictions that apply to the sequential organization of phonemes allowed within the words of their native language, that is, its phonotactic properties. As previously mentioned, the present dissertation focuses on infants' capacity to learn non-adjacent phonotactic properties of their native language. Accordingly, the following section presents a review of the literature regarding infants' phonotactic acquisition.

The case of phonotactic information

Phonotactic information makes reference to the possible combinations of phonemes in order to form syllables, morphemes or words, thus, to the sound regularities and restrictions applying in a given language. These phoneme relations can be adjacent, that is between consecutive phonemes, or they can be non-adjacent, when referring to a dependency between two phonemes that are not consecutive, because there is one or more phonemes intervening between the dependent phonemes (i.e. in the construction BvT, such as the word /bat/, the consonantal phonemes /B/ and /T/ are not consecutive because they are separated by a vowel).

Almost all the research at this level has focused on adjacent constructions. Regarding early sensitivity to syllabic structure, Bertoncini and Mehler (1981) conducted a study with 2-month-old infants, who were presented with either stimuli with a syllabic structure CVC (/pat/, /tap/) or stimuli with a non-syllabic structure CCC (/tsp/, /pst/). The results indicated that stimuli with a syllabic structure were better discriminated than non-syllabic stimuli, showing the existence of an early sensitivity to the “good” syllabic structures that would be universal.

Regarding acquisition, on the one hand, Jusczyk and colleagues (1993) found that 9-month-old English as well as Dutch infants prefer to listen to a list of words corresponding to the phonetic and phonotactic structure of their language (English/Dutch) rather than to a list of words with a structure of the other language. Furthermore, similar effects were found by Friederici and Wessels (1993), who showed that 9-month-old Dutch infants are sensitive to the phonotactic clusters of their language, preferring to listen to legal rather than illegal clusters. No similar effects were found with younger infants (4.5- and 6-month-olds). Sebastián-Gallés and Bosch (2002) also showed sensitivity to phonotactic clusters: 10-month-old Catalan infants showed a preference for CVCC stimuli having a legal phonotactic cluster in Catalan compared to illegal ones. The same pattern was found in Catalan/Spanish bilingual infants growing up in a Catalan predominant environment. Taken together, these results show that infants start acquiring knowledge about the permissible adjacent sound sequences of their native language around 9 months of age.

On the other hand, Jusczyk et al. (1994) have shown that infants can not only distinguish between legal and illegal sound sequences, but they are also sensitive to the frequency of occurrence of legal structures. Using the head-turn preference procedure, they tested English-learning infants using a list of words having low-probability sequences (i.e. “yush”, “shibe”, “cherg”), and a list of words having high-probability sequences (i.e. “chun”, “tyce”, “keek”). The probability of a sound sequence was defined based on the positional phoneme frequencies of each phoneme (i.e. in /kik/, /k/ is frequent in onset and coda position and /i/ is frequent in middle position), and on the biphone frequencies of C_1V_1 and V_1C_2 according to English phonotactic structure. Their results showed that 9- but not 6-month-old English infants have a preference for sound sequences with a high phonotactic probability in their language, compared with sound sequences that exhibit a low probability.

Taken together, the studies described above indicate that around 9 months, infants become attuned to the phonotactic properties of their native language. Infants start preferring the structures that are either legal or more frequent in their native language. However, all of these phonotactic findings are restricted to infants' sensitivity to adjacent properties. Given that languages also instantiate dependencies between non-adjacent elements, the mechanisms used for language acquisition should also be able, at some point, to learn non-adjacent dependencies (Chomsky, 1957; Miller & Chomsky, 1963). This dissertation investigates whether, and if so when, infants become sensitive to non-adjacent phonotactic dependencies. Therefore, the next section presents a review of the literature focusing on non-adjacent acquisition.

Sensitivity to non-adjacent phonotactic dependencies

Languages embed many non-adjacent dependencies at different levels. In the morphosyntaxic domain, the examples of non-adjacent dependencies are quite numerous, such as subject/verb agreement (i.e. the cat eats …; Nazzi, Barrière, Goyet, Kresh, & Legendre, 2011; Newport & Aslin, 2004), number agreement (i.e. The boys living next door are…; Farkas, in press; Gomez, 2002), and dependencies between auxiliaries and inflectional morphemes (i.e. is sleeping, has arrived; Santelmann & Jusczyk, 1998; Gomez, 2002; Pacton & Perruchet, 2008; Farkas, 2009). In addition, non-adjacent dependencies can be found in centre-embedded sentences (i.e. the rat the cat ate stole the cheese, Pacton & Perruchet, 2008), as well as in wh-question words that replace noun phrases much later in the sentence (Newport & Aslin, 2004). Non-adjacent dependencies have been also suggested to be crucial in the acquisition of syntactic category structure (Mintz, 2002, 2003; Onnis Monaghan, Richmond, & Carter, 2005).

Accordingly, various artificial language studies in the morphosyntactic domain have shown that adults, young children, and infants are capable of rapidly learning consistent relationships among temporally adjacent speech sounds or musical tones and of grouping these elements into larger coherent units such as words or melodies (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996; Gomez & Gerken, 1999; Mintz, 1996). However, Newport and Aslin (2004) showed that adults cannot learn patterns between non-adjacent syllables (i.e. gu_do), while they can easily learn dependencies between non-adjacent phonemic segments (i.e. p_g_t_). This is in line with the fact that natural languages usually exhibit non-adjacent dependencies between segments (consonants or vowels, i.e. Semitic languages, see details below) but rarely between syllables (Newport & Aslin, 2004).

Furthermore, different studies have shown that adults and 18-month-old infants are able to learn artificial (AxC) grammar instantiating non-adjacent dependencies, that is, sequences in which the first element predicts the third element (i.e. pel wadim rud; Gomez, 2002). In a subsequent study using the same kind of grammar, Gomez and Maye (2005) showed that 15-month-old infants were also able to learn rules involving non-adjacent dependencies, but 12 month-olds were only able to learn rules involving adjacent dependencies.

In the phonological domain, non-adjacent dependencies are also found, for example in terms of sound assimilation. For instance, many languages such as Khalkha, Mongolian, Yaka, Finish, Hungarian and Turkish (Nguyen, Fagyal, & Cole, 2008; Goldsmith, 1985; Meyer, 2007) exhibit vowel harmony, in the sense that vowels separated by consonants necessarily share a given phonetic feature within words. Turkish, for example, presents front/back harmony, according to which words cannot contain both front and back vowels. Consonant harmony can also be found in some languages such as Navajo (Young & Morgan, 1987; McDonough, 2003), though this is crosslinguistically less frequent (some languages in fact favoring consonant disharmony, Nespor, Peña, & Mehler, 2003).

Besides vocalic harmony, non-adjacent phonological dependencies can also be found in Semitic languages as Hebrew and Arabic, in which lexical roots are made of non-adjacent sound patterns. In these languages, verbs are built from a consonant pattern such as k-t-b, and different verb forms are derived by inserting vowel patterns between the consonants to indicate tense, number… (Creel, Newport, & Aslin, 2004; Newport & Aslin, 2004).

Furthermore, non-adjacent dependencies have been found to affect adult lexical processing (Kager & Shatzman, 2007; Suomi, McQueen, & Cutler, 1997), to facilitate the acquisition of phonotactic rules and, in some circumstances, the learning of words and rules from continuous speech streams (Onnis, et al., 2005; Bonatti, Peña, Nespor, & Mehler, 2005).

In spite of all this literature on non-adjacent phonological phenomena, there is only one infant study in the domain of phonetics and phonotactics that has focused on the acquisition of non-adjacent dependencies. Nazzi, Bertoncini, and Bijeljac-Babic (2009) conducted a study aiming at exploring the age at which infants start preferring to listen to words containing non-adjacent structures with high frequency in the language, compared to structures having low frequency. More specifically, they explored whether 6- and 10-month-old French-learning infants have a preference for labial-coronal (LC) structures over coronal-labial (CL) ones, which are structures differing in the relative order of their non-consecutive labial (like /p/ or /b/) or coronal (like /t/ or /d/) consonants. These structures were chosen due to the linguistic effect known as the “Labial-Coronal bias”.

The Labial-Coronal bias

Different typological studies have evidenced the existence of various phonotactic tendencies that are consistent across languages. Among these dependencies, languages have been shown to privilege sequences starting with a labial consonant followed by a coronal consonant over the opposite pattern (/bat/ rather than /tap/; Ingram, 1974; MacNeilage, Davis, Kinney, & Matyear, 1999; MacNeilage & Davis, 2000; Vallée, Rousset, & Boë, 2001). This phenomenon is known as “the labial-coronal effect”.

This effect was initially reported in young children’s early productions. Ingram (1974) studied the early productions of two children, one English and one French. His results showed a tendency for both infants to produce more words beginning with a labial consonant followed by a posterior consonant than the opposite pattern. This "anterior-to-posterior progression" was also found by Locke (1983), and was later confirmed by MacNeilage, Davis, Kinney, and Matyear (1999) testing a larger sample of infants. MacNeilage and colleagues (1999) observed that during the 50-word-stage (12-18 months), English-learning infants tend to produce 2.55 times more Labial-Coronal (LC) than Coronal-Labial structures. This tendency was found in 9 out of the 10 infants tested, and it was confirmed in other languages, such as German, Dutch, French, and Czech (MacNeilage & Davis, 1998).

Different motor accounts have been proposed to explain this effect. First MacNeilage and Davis (2000) suggested the existence of a self-organizational tendency in infants to begin utterances with an easy element and then to add complexity. According to their frame-content theory, a labial CV sequence is defined as the default, being a pure frame that results from a simple mandibular oscillation, while a coronal CV sequence or fronted frame needs an additional tongue movement. Given infants' tendency to start sequences with an easy element and then to add complexity, they should produce more labial-coronal CV-CV sequences (easy-complex) than coronal-labial CV-CV ones (complex-easy), as observed in their early production studies.

A second explanation for the LC bias, also based on motor constraints, proposes that this preference can be explained as a reflection of an articulatory preference for the LC form that would be better synchronized than the CL form. Sato, Vallée, Schwartz, and Rousset (2007) remarked that the explanation proposed by MacNeilage and Davis (2000) seems *ad hoc*, given that Vilain, Abry, Badin, and Brosda (1999) have demonstrate that a mandibular oscillation can produce both a labial CV and a coronal CV sequence. Therefore, the frame content theory cannot explain per se the LC bias according to these authors. Rochet-Capellan and Schwartz (2005a; 2005b) thus proposed an alternative explanation, known as the “Labial-Coronal Chunking Hypothesis”. This hypothesis is based on adult speeded articulation tasks in which it was found that speeding the pronunciation of a $C_1V_1C_2V_2$ sequence leads to a shift from one jaw cycle per syllable to one per disyllable by reducing the vowel after one of the consonants (i.e. /boto/ evolving into /b'to/). When producing such a sequence, there is generally a gestural overlap, as the onset of C_2 precedes the offset of C_1. Different studies have shown that this gestural overlap is longer when C_1 is anterior to C_2, compared to the opposite case when C_1 is posterior to C_2. Given that labial consonants are anterior to coronal consonants, gestural overlap is longer in an LC sequence than in a CL sequence. It was hypothesized that having a longer overlap allows better synchronization between the labial and the coronal consonants in an LC compared to a CL sequence, resulting in the LC bias (Sato, et al., 2007). This was confirmed in adult speeded articulation tasks where adults were presented with $C_1V_1C_2V_2$ sequences containing a labial and a coronal consonant. Results showed that LC shifts were favored over CL shifts, LC $C_1V_1C_2V_2$ sequences become to LC $C_1C_2V_2$ sequences (i.e. /pata/→/p'ta/) and CL $C_1V_1C_2V_2$ sequences change into LC $C_1C_2V_2$ sequences /tapa/→/p'ta/), demonstrating that LC sequences have higher articulatory stability than CL sequences (Rochet-Capellan & Schwartz, 2007).

A third explanation to the LC bias has been proposed, according to which the LC bias would be explained by the relation that exists between perceptual acquisition and frequency in the input. In other words, there would exist a relation between the preference for certain sound sequences and their frequency in the language (as shown in adjacent phonotactic acquisition studies reviewed earlier). According to this hypothesis, the fact that LC structures are more frequent than CL structures in the lexicon of many languages could explain infants' preference for these structures. In relation to this, two different studies have analyzed the frequency of LC and CL structures in the following languages: English, Estonian, French, German, Hebrew, Japanese, Maori, Quechua, Spanish and Swahili (MacNeilage, et al., 1999); Afar, Finnish, French, Kannada, Kwalkw'ala, Navaho, Ngizim, Quechua, Sora and Yup'ik (Vallée, Rousset, & Boë, 2001). These studies showed that in all languages but Japanese and Swahili, LC sequences are significantly more frequent than CL ones.

In French, the proportion of LC/CL structures have been analyzed by Vallée et al. (2001) based on the BDLex corpus, which is a lexical database of spoken and written French containing 440.000 words (50.000 lemmas; de Calmès & Pérennou, 1998). They found that LC structures are more frequent among the onset of consecutive syllables (1.69 ratio in word onsets; 1.56 ratio overall) and between the onset and the coda of a same syllable (2.9 ratio in word onsets; 2.29 ratio overall). Furthermore, the LC advantage is not solely due to a larger proportion of words beginning with a labial consonant. A count in BDLex indicates that there are 6328 L-initial words and 6545

C-initial words in this French database, suggesting that the LC asymmetry really reflects the predominance of LC combinations compared to CL ones.

We conducted an analysis on a different database: Lexique 3, which provides the written frequency in French of 135.000 words (55.000 lemmas), calculated on the basis of the 15 millions words contained in the database (New, Pallier, Ferrand, & Matos, 2001). This analysis allowed us to compute the number of words, but also the frequency of occurrence of different phonemic sequences. Our analysis revealed an advantage for LC sequences in terms of number, but also in terms of frequency. This is the case in the overall analysis, but also when the analysis was restricted to word onsets or to CVC words (Table 1). These results confirmed and extended the biases found by Vallée et al. (2001).

Table 1. Cumulative frequency of LC and CL French words (all words, word-onset and CVC words only) according to the adult database *Lexique 3* (New, et al., 2001)

	Frequency			Number		
	Overall	Word Onset	CVC Words	Overall	Word Onset	CVC Words
Labial-Coronal	71,822	45,323	6,808	13,746	5,545	262
Coronal-Labial	42,772	16,144	1,180	8,838	2,720	90

In addition, an analysis of the L-initial/C-initial words and L-final/C-final words revealed the existence of asymmetries between labial and coronal consonants (c.f. Table 2). Even if the numbers of L-initial and C-initial words that we obtained differs from the one obtained by Vallée and colleagues (2001), the relation between both numbers is basically the same: 13’405 L-initial words and 13’358 C-initial words. However, if we analyze the data in terms of frequency, it appears that C-initial words are much more frequent than L-initial words (306’040 *versus* 187’137 respectively). An asymmetry in favor of coronal consonants is also present in word coda position, both for number of words (11’072 C-final words and 2’659 L-final words) and in terms of their frequency (125’184 C-final words *versus* 19’272 L-final words).

Table 2. Comparative analysis in terms of cumulative frequency of words starting or ending with a Labial or a Coronal consonant in the French Lexique 3 database (New, et al., 2001).

	Onset position				Coda position			
	Overall		CVC words		Overall		CVC words	
	Frequency	Number	Frequency	Number	Frequency	Number	Frequency	Number
Labial	187,137	13,405	37,140	144	19,272	2,659	1,745	32
Coronal	306,040	13,358	165,813	222	125,184	11,072	44,359	89

To sum up, according to our analyses, the LC bias cannot be reduced to positional phoneme frequencies, such as L-initial or C-final biases, but it truly reflects a non-adjacent dependency, marked by an advantage of LC combinations over CL ones, both in terms of word numbers and frequencies. These results are in line with the results obtained by Vallée et al. (2001). Nevertheless, it is important to keep in mind that in spite of this LC bias, the French lexicon exhibits a C-initial and a C-final bias. Therefore, the existence of these coronal advantages will have to be kept in mind in experimental designs, to determine whether or not these coronal biases influence the perceptual preference for LC sequences (see experimental part 1.1, control experiments 2a-3b).

The present work continues to explore the perception of LC and CL non-adjacent structures in different directions, taking as a point of departure the study conducted by Nazzi et al. (2009). Accordingly, we now present this study in more details.

The goal of Nazzi et al. (2009) was to determine whether or not a perceptual LC bias is present during infancy, and whether such an effect is part of infants' early sensitivities or whether it is the result of a linguistic acquisition process. The authors tested French-learning infants' listening preference for LC and CL sequences at 6 and 10 months of age, using the HPP method. They found that infants listen significantly longer to LC sequences compared to CL ones at 10 months ($p = .004$) but not at 6 months ($p = .60$; see Fig. 1). This preference pattern was found in 13 out of the 16 10-month-olds.

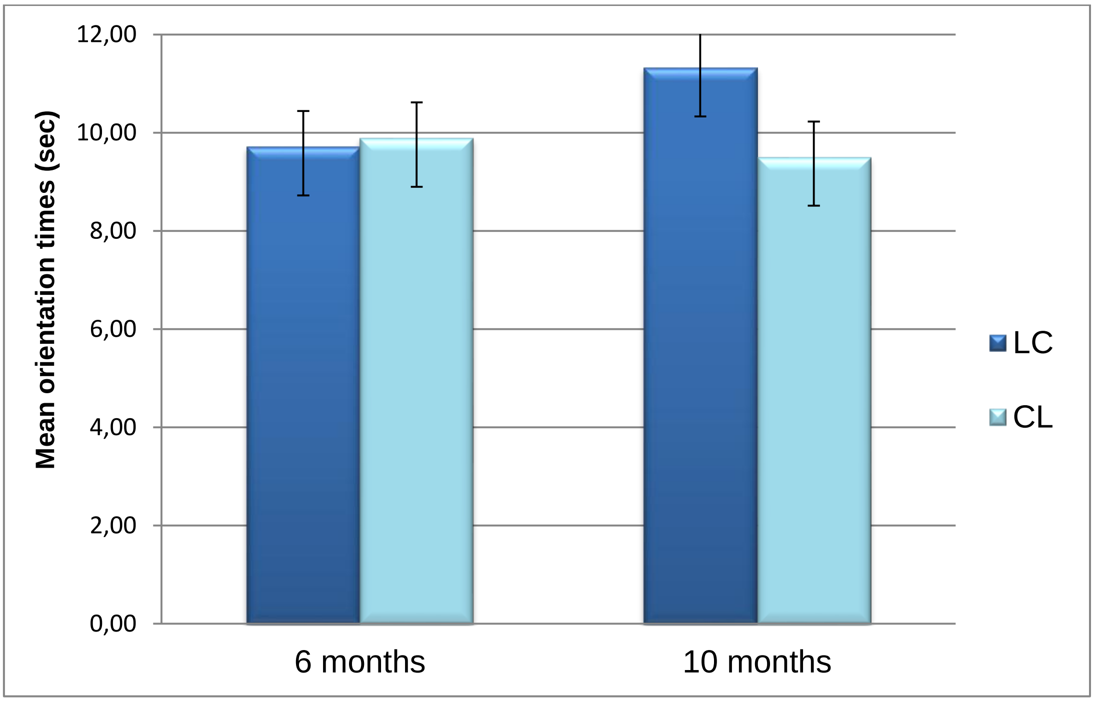


Figure 1. Mean orientation times (and SE) to LC and CL words in Nazzi et al. (2009).

Based on these results, Nazzi et al. (2009) concluded that during the second part of the first year of life, infants start preferring the structures that are more frequent in their native language. In this particular case, the preference for words having an LC structure could reflect a phonological acquisition, resulting from exposure and processing of the native language. Thus, it is possible that the LC bias found in children's early productions results from perceptual acquisition and not from motor constraints, as MacNeilage and Davis (2000) proposed. In addition, the most important implication of Nazzi et al. (2009) was the suggestion that between 6 and 10 months of age infants become sensitive to dependencies between non-adjacent elements in a word (in this case two consonants separated by a vowel).

However, two features of that study prevent us from making strong conclusions about the acquisition of non-adjacent dependencies. First, Nazzi et al. (2009) used disyllabic stimuli. Therefore, the LC bias found in that study could have resulted from the acquisition of dependencies between two adjacent syllables. Second, we conducted a frequency analysis of their stimuli at three different levels: disyllabic words ($C_1V_1C_2V_2$), triphones ($C_1V_1C_2$ and $V_1C_2V_2$) and diphones (C_1V_1, V_1C_2 and C_2V_2). The comparison between words' adjacent frequencies (see Table 3) showed that these stimuli not only presented differences in terms of non-adjacent dependencies (LC bias) but they also differed in terms of adjacent dependencies, which were generally higher for the LC words, and significantly so for the last pair of phonemes (second consonant + final vowel: C_2-V_2). These differences in adjacent frequencies might eventually have played a role on the preference for the LC sequences found by Nazzi et al. (2009).

Table 3. Comparative analysis of cumulative frequency of LC and CL stimuli used in Nazzi et al. (2009) conducted in the Lexique 3 database (New, et al., 2001).

LC	$^{*}\mathrm{L}^{\mathrm{v}*}$		$^{*\mathrm{v}}\underline{\mathrm{C}}^{*}$		$^{*}\underline{\mathrm{C}}^{\mathrm{v}*}$		$^{*}\mathrm{L}^{\mathrm{v}}\mathrm{C}^{*}$		$^{*\mathrm{v}}\mathrm{C}^{\mathrm{v}*}$		$^{*}\mathrm{LvCv}^{*}$	
bateau	ba	3816	at	9552	to	645	bat	11706	ateau	993	bateau	175
baudet	bo	993	od	226	de	12654	baud	38	aude	601	baude	1
bedeau	be	1699	ed	360	do	705	bed	14	edeau	284	bedeau	4
bouder	bou	2660	oud	619	de	1515	boud	219	oude	202	bouder	40
bouton	bou	2660	out	3129	ton	1239	bout	1371	outon	1057	bouton	91
butée	bu	1030	ut	1656	té	17547	but	1279	utée	1571	butée	251
paddy	pa	22542	ad	3304	di	6274	pad	59	addy	903	paddy	1
patin	pa	22542	at	9552	tin	1966	pat	2119	atin	2848	patin	12
panda	pan	2267	and	6873	da	6873	pand	4850	anda	3737	panda	7
piteux	pi	2635	it	8526	teu	897	pit	3604	iteu	129	piteu	22
pédant	pé	4515	éd	22910	dan	10342	péd	7	édan	490	pédan	11
potée	po	3435	po	3435	té	17547	pot	582	otée	6831	potée	158
Mean LC		5899		5845		6517		2154		1637		64

CL	$^{*}\mathrm{C}^{\mathrm{v}*}$		$^{*\mathrm{v}}\underline{\mathrm{L}}^{*}$		$^{*}\underline{\mathrm{L}}^{\mathrm{v}*}$		*CvL*		$^{*\mathrm{v}}\underline{\mathrm{L}}^{\mathrm{v}*}$		*CvLv*	
dauber	do	705	ob	454	be	1699	daub	4	aube	1620	daube	0.40
debout	de	1515	eb	977	bou	2660	deb	164	ebou	211	debou	160
début	de	6115	éb	9079	bu	1030	déb	6626	ébu	637	débu	456
dépit	de	6115	ép	9079	pi	2635	dép	10658	épi	679	dépi	64
dépot	de	6115	ép	9079	po	3435	dép	10658	épo	359	dépo	82
dopant	do	2585	op	852	pan	2267	dop	4	opan	1	dopan	1
tabou	ta	8367	ab	5238	bou	2660	tab	4224	abou	1012	tabou	48
tapis	ta	8367	ap	7677	pi	2635	tap	2789	api	1739	tapi	400
taupin	to	645	op	852	pin	684	taup	295	aupin	216	taupin	0.07
tomber	ton	1239	onb	1812	bé	1699	tomb	16006	ombe	3241	tombe	3084
toupet	tou	13815	oup	1184	pé	3582	toup	28	oupe	1054	toupe	5
tuba	tu	5765	ub	595	ba	3816	tub	286	uba	56	tuba	22
Mean CL		5112		3906		2400		4312		902		360
P value		.71		.45		.004		.30		.32		.28

Therefore, because of the differences in adjacent frequencies and the use of disyllabic stimuli, it cannot be concluded that infants in Nazzi et al. (2009) were reacting to non-adjacent dependencies. Therefore, there is no conclusive evidence showing that infants are sensitive to non-adjacent phonological dependencies early in development. Establishing such acquisitions is crucial given the pervasiveness of nonadjacent dependencies, which are a key feature in human languages both at the phonological level, but also at the syntactic/morphosyntactic level. For that reason, the first goal of the present dissertation focuses on this issue.

Dissertation Goal 1

The first experimental part of the present dissertation focuses on infants' acquisition of non-adjacent phonological dependencies, with three main aims:

- Establish whether (and if so, when) infants are sensitive to non-adjacent phonotactical dependencies
- Explore the level at which these dependencies are acquired
- Specify the mechanisms underlying the acquisition of such phonological properties.

From speech perception to lexical acquisition

As previously reviewed, infants start acquiring during the second half of their first year of life the prosodic, phonetic, and phonotactic properties of their native language (Jusczyk, et al., 1993b; Höhle, et al., 2009; Friederici & Wessels, 1993; Werker & Tees, 1984; Kuhl et al., 1992; Jusczyk, et al., 1994). Even if all these acquisitions are extremely important, they are not sufficient per se to start communicating with others. In the complex process of language acquisition, infants also have to discover what is and what is not a word-like unit, thus they have to segment word forms from the speech stream. In parallel, they also have to associate those word-like units with meaning representations. During the second experimental part of this dissertation, we will be focusing on the link that exists between early speech perception and lexical acquisition. On the one hand, we will explore word segmentation and on the other hand we will study word learning. Accordingly, we now briefly review relevant elements regarding what is known about the development of these two processes.

Word-segmentation

Spoken language is in large parts a continuous speech stream. It contains strings of sound sequences without any systematic marker of where word boundaries are. To acquire a language infants have to deal with this stream, trying to find different cues to what is and what is not a word-like unit. Different phonological regularities have been found to be particularly important for word segmentation (for a review see Mattys, White, & Melhorn, 2005). The first one is transitional probabilities (TPs), defined as the normalized version of the probability of event Y given event X, and classically calculated according to the following formula: $\mathrm{TP}(\mathrm{Y}|\mathrm{X}) = \frac{\text{frequency (XY)}}{\text{frequency (X)}}$ (Goodsitt, Morgan, & Kuhl, 1993; Brent & Cartwright, 1996; Saffran, Aslin, & Newport, 1996; Johnson & Tyler, 2010; Mersad & Nazzi, 2012). The second one refers to prosodic regularities, such as the rhythmic unit of a given language, like the trochaic (strong-weak) unit for stressed-based languages such as English or Dutch (Echols, Crowhurst, & Childers, 1997; Jusczyk, Houston, & Newsome, 1999; Houston, Jusczyk, Kuijpers, Coolen, & Cutler, 2000; Kooijman, Hagoort, & Cutler, 2009; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel, & Jusczyk, 2005), or the syllabic unit for syllable-based languages such as French (Goyet, de Schonen, & Nazzi, 2010; Mersad, Goyet, & Nazzi, 2010/2011; Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006; Polka & Sundara, 2012). A third cue is allophonic variations, that is the fact that some phonemes are pronounced in a different way depending on their position in a word, such as in English /p/ which is pronounced as /p^h/ in pen, but as /p/ in spike (Jusczyk, Hohne, & Baumann, 1999; Mattys & Jusczyk, 2001b). Finally, languages also have different phonotactic regularities, thus set of phonemes that can continuously or distantly occur within a word unit. For example, in English /zt/ is not allowed inside a word, but /st/ is a legal sequence, as these two phonemes can co-occur in the words like *stamp* or *street*. Conversely, being an illegal sequence within words, /zt/ can be a cue to a boundary between two words. Infants could thus hypothesize that when hearing a /zt/ sequence, /z/ is the coda of a word and /t/ is the onset of the following word (Mattys, et al., 1999; Mattys & Jusczyk, 2001a).

It is important to highlight that none of these cues is sufficient to find all word boundaries within an utterrance. Therefore, infants have to use them in combinations to successfully segment speech (Christiansen, Allen, & Seidenberg, 1998). In addition given that prosodic characteristics, allophonic variations and phonotactic regularities are all language-specific, that is, that they vary between languages, infants first have to detect and learn these cues from the speech signal in order to later use them to segment words.

At present, there is ample evidence suggesting that, early in life, infants start exploiting regularities in their native language to find word boundaries. Jusczyk and Aslin (1995) initially showed that 7.5- but not 6-month-old infants prefer to listen to passages containing words presented during a familiarization phase than passages with control words. This means that these infants were able to recognize the target words in the passages, implying that they were able to extract them from the rest of the sentences. In other words infants succeed at segmenting target words by 7.5 months. Using this paradigm, different studies have explored the kind of regularities that infants use to segment words from the speech stream.

First, regarding prosodic cues, Jusczyk, Houston, and Newsome (1999) showed that infants use the rhythmic unit of their native language to segment words. Indeed, 7.5-month-olds segmented words having a trochaic (strong-weak) stress pattern, which is the typical stress pattern of English, as English words are usually stressed on their first syllable. However, infants were not able to segment words with an iambic (weak-strong) stress pattern until some months later, by 10.5 months. This shows that English-learning infants rely on the trochaic unit for word segmentation. On the other side, by 8 months of age, French-learning infants have been found to rely on the syllable unit to segment words from fluent speech, the syllable corresponding to the rhythmic unit of French (Goyet, de Schonen, & Nazzi, 2010; Goyet, Nishibayashi, & Nazzi, in preparation; Mersad, Goyet, & Nazzi, 2010/2011; Nazzi, et al., 2006; Polka & Sundara, 2012). Other studies confirmed that infants use the rhythmic unit of their native language to segment words (Morgan & Saffran, 1995; Echols, et al., 1997; Johnson & Jusczyk, 2001; Curtin, Mintz, & Christiansen, 2005; Houston, Santelmann, & Jusczyk, 2004; Nazzi, et al., 2005).

Second, Safran, Aslin, and Newport (1996) found that 8-month-old infants are also able to segment words using distributional cues. In their study, infants were familiarized for two minutes with an artificial language stream containing 4 words (tupiro, golabu, bidaku, and padoti), words being defined as chains of 3 syllables always occurring together (TPs = 1). Each word was alternatively followed by one of the other 3 words (TPs = 1/3). During the familiarization phase, infants listened to a continuous speech stream containing in chain the four words of the artificial language (i.e. padotigolabubidakupadotitupirobidakugolabutupiro). The only available cue for word boundaries were the differences in transitional probabilities between syllables ($TPs_{within\ words}$= 1, $TPs_{between\ words}$= 1/3). During the test phase, infants were presented with a list containing the words of the artificial language (tupiro, golabu, padoti, bidaku …) and a list of part-words, that is 3-syllable chains spanning two different words of the artificial language (dotigo, dakutu…). Results showed that infants were able to distinguish the words from the part-words, reflecting their ability to compute TPs, and to use these distributional cues to segment words.

Third, Jusczyk, Hohne, and Baumann (1999) showed that 10.5-month-old infants are able to segment words from fluent speech using solely allophonic cues. The authors familiarized half of the infants with one of two sequences (nitrate / night rate), which are pronounced almost in the same way (/naɪtreɪt/, /naɪt reɪt/), but these sequences contained allophonic variants. In the word “nitrate,” the first /t/ is aspirated, released, and retroflexed, whereas the /r/ is devoiced, suggesting that it is part of a cluster. By comparison, the first /t/ in “night rate” is unaspirated and unreleased, suggesting that it is syllable final, whereas the following /r/ is voiced, suggesting that it is syllable initial (Jusczyk, Hohne, & Baumann, 1999, p. 1467). Additionally, infants were also familiarized with one of the two control words (hamlet or doctor). Then, authors analyzed infants’ ability to detect these sequences inserted in fluent speech contexts. During the test phase, all infants were presented with four different passages, each containing one of the two words used during familiarization and two other control words (nitrates/hamlet versus night rates/doctor). The results showed that at 10.5, but not at 9 months of age, infants perceive differently the passages containing the words nitrate and night rate, indicating that they are able to distinguish both sequences. Taken together, these results show that infants are sensitive to allophonic variations and that they can use these cues to detect words in fluent speech contexts. These results are in line with other studies also showing that infants can segment words using allophonic cues (Mattys & Jusczyk, 2001b) and with studies showing that infants are sensitive to allophonic variations very early in life (Hohne & Jusczyk, 1994; Christophe, Dupoux, Bertoncini, & Mehler, 1994).

Fourth, Mattys and Jusczyk (2001a) showed that infants can also use phonotactic regularities when segmenting speech. Infants were familiarized with a passage in which the target word was surrounded by a cluster with high-probability between words and a passage where the target word was surrounded by sound sentences lacking such phonotactic cues. Then, infants were presented with a list containing different tokens of the target word surrounded by phonotactic cues, a list with the target word surrounded by a context lacking such cues, and two control words that were not presented during familiarization. The results showed a significant preference for the words presented in the phonotactic context with high-probability between words, suggesting that 9-month-old infants use probabilistic phonotactics to find word boundaries. These results line up with evidence showing that around 9 months, infants become sensitive to the phonotactic properties of their native language (Jusczyk, et al., 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002; Jusczyk, et al., 1994).

The studies presented above establish that infants use their prior knowledge about the prosodic, distributional, allophonic and phonotactic characteristics of their native language to find word boundaries. However, all this evidence relates to adjacent acquisitions. To the best of our knowledge, there are no studies exploring the link existing between infants' prior knowledge about non-adjacent phonotactic dependencies in their native language and their word segmentation abilities. This gap prompted us to add another goal to our study.

Dissertation Goal 2

In the second experimental part of this dissertation, we will explore whether, and if so, when in development, prior knowledge about non-adjacent phonological acquisitions influences later lexical acquisition and, more specifically, word segmentation.

Word-learning

Once an infant has discovered a word-like unit s/he will have to associate this word-like unit with its meaning representation. The process of mapping sound sequences with meaning representations is known as word learning (Gogate, Walker-Andrews, & Bahrick, 2001; Hollich, et al., 2000; Schafer & Plunkett, 1998; Werker Cohen, Lloyd, Casasola, & Stager, 1998; Yoshida, Fennell, Swingley, & Werker, 2009).

Tincoff and Jusczyk (1999; 2011) found evidence showing some word comprehension as early as 6 months of age. Using an intermodal preferential looking paradigm, Tincoff and Jusczyk (1999) presented infants with side-by-side videos of their parents first in silence, then while playing the word “mommy” or the word “daddy”. Their results showed that infants looked significantly longer to their mother video when they listened to the word “mommy” and they looked significantly longer to their father video when they listened to the word “daddy”. In an additional experiment, Tincoff and Jusczyk (1999) showed that infants link the words “daddy” and “mommy” to their own parents, rather than to male versus female persons. In a subsequent study using the same paradigm, Tincoff and Jusczyk (2011) showed that 6-month-olds have already associated sound sequences to meaning representations for some other frequent words such as “hand” and “feet”. Similar results have been recently found, showing that 6- to 9-month-olds already know the meaning of several ordinary words such as food-related and body-part words (Bergelson & Swingley, 2012).

In addition, there is some evidence showing that well before their first birthday infants are able to learn associations between sounds and objects in laboratory tasks (Gogate & Bahrick, 1998; Gogate, 2010). Gogate and Bahrick (1998) habituated 7-month-old infants with videos of novel objects that were matched with either the vowel /a/ or /i/. There were three different conditions: one in which the object moved in synchrony with the vowel vocalizations (moving synchronous condition), one with no object movement (still condition), and one in which the object moved asynchronously with the vowel vocalizations (moving-asynchronous condition). During the test phase, infants received four test trials. In two of them, the vowel-object pairs were consistent with the training (control trials) and in the other two trials the vowel-object pairs were inconsistent (mismatch trials). The results showed that 7-month-old infants significantly increase their looking times during the mismatch trials, but only in the moving synchronous condition. These results show that 7-month-olds are able to associate simple sounds, like vowels, with novel objects when the movement of the object is coherent with the sound presentation. Gogate (2010) extended these results by testing 7- and 8-month-old infants, using the same kind of paradigm. However, this time, infants were not presented with vowels but with more complex sound sequences (i.e. /tah/, /gih/). In this study, only 8-month-olds were able to associate these sound sequences to their referent objects, again only in the moving synchronous condition.

It is by 12 months of age when infants are able to associate a novel word to a novel object, even in the absence of synchronous movement, if this learning is supported by social cues (such as eye gaze, pointing, handling; Hollich, et al., 2000). Moreover, by 14 months, infants start succeeding in word-learning tasks even in the absence of social cues (Werker, et al., 1998). In that study, infants were first habituated with two novel word-object combinations in a semi-random order, until their looking time decreased to a set criterion or until they reached 20 trials. After infants were habituated, they were tested with two trials: one consistent with the word-object pairings of the habituation phase, and another inconsistent one. Results showed that 14- but not 8-, 10-, or 12-month-olds were able to associate novel words (i.e. neem versus lif) with their referent objects when the target words were phonetically very contrasted.

At this point, it is clear that at the onset of the second year of life infants are able to map sound sequences with meaning representations (Werker, et al., 1998; Gogate & Bahrick, 1998; Schafer & Plunkett, 1998; Hollich, et al., 2000; Gogate, et al., 2001; Yoshida, et al., 2009; Havy & Nazzi, 2009; Gogate, 2010; Bergelson & Swingley, 2012). In this context, the third part of the present dissertation will focus on the link that exists between phonotactic knowledge and lexical acquisition. Accordingly, the following paragraphs briefly review the literature on this topic.

Most of the evidence showing that phonotactic knowledge can affect word learning comes from studies conducted with children or adults. For children, studies have shown that children between 3 and 13 years can learn novel words more readily when labels contain frequent sound sequences compared with labels containing infrequent sound sequences, frequencies being based on phone and biphone positional phonotactic probabilities (i.e. common sound sequences such as /wæt/ versus rare sound sequences such as /naʊb/; Storkel & Rogers, 2000; Storkel, 2001; 2003; 2004). In addition, children can repeat non-words with high phonotactic probabilities more accurately than non-words with low probabilities (Gathercole, 1995; Edwards, Beckman, & Munson, 2004) and these high-probability non-words are also better recalled (Gathercole, Frankish, Pickering, & Peaker, 1999). For adults, evidence shows that they repeat high-probability non-words faster than low-probability non-words (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997; Vitevitch, Luce, Pisoni, & Auer, 1999; Vitevitch, & Luce, 2005). In addition high-probability non-words are rated to be more word-like than low-probability non-words (Frisch, Large, & Prisoni, 2000; Treiman, Kessler, Knewasser Tincoff, & Bowman, 2000; Bailey & Hahn, 2001).

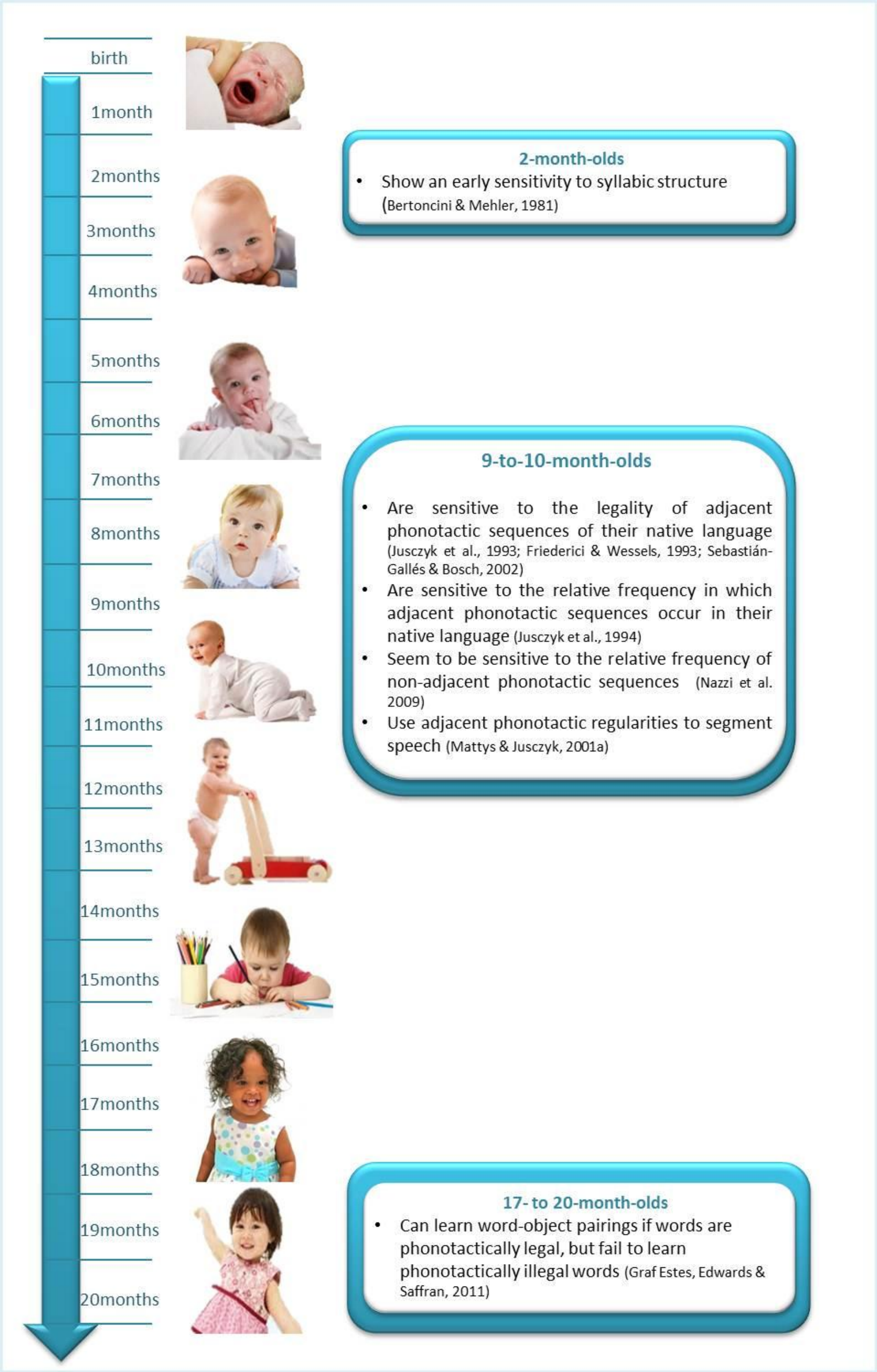
All these pieces of evidence indicate that phonotactic knowledge can affect word processing in children and adults. What about early word learning? To the best of our knowledge, only one study by Graf Estes, Edwards, and Saffran (2011) has focused on this issue. In that study, they tested infants' ability to associate novel words with novel objects when the labels were either phonotactically legal or illegal in English, the native language of the infants. To do so, infants were presented with two novel object-label pairs. For one group of infants, these labels were phonotactically legal (dref or sloob) while for the other group, they were phonotactically illegal (dlef or sroob). Infants were also presented with 2 pairs of familiar object-label pairs to add variety to the task and to give infants a familiar context for the labeling. The learning phase consisted of 12 trials (8 for the novel object-label pairs and 4 for the familiar object-label pairs). Within each trial, the infants saw the image of an object moving side-to-side while a female voice said: "Look at the (target)!, It's a (target)!, See the (target)?, That's a (target)!''. After the learning phase, a static image showing both novel objects or both familiar objects (one on each side of the screen) was presented first in silence, then following a voice requesting one of the objects: ''Where's the (target)? Do you like it?''. The results looking at infants' proportion of fixation time to the target object showed that 17-to-20-month-old infants are able to learn the word-object pairings in the phonotactically legal condition, but they failed in the phonotactically illegal condition. These results show that phonotactic knowledge constrains to a certain extent early word acquisition.

However, at present, the scope of these constraints remains undetermined. Further studies need to be conducted to determine whether these effects are limited to legal versus illegal sound sequences, considering that both sequences may not be processed in the same way (given that sound sequences in illegal items have never been heard in word-like units in the input), or whether these effects can be extended to high versus low phonotactic probability sequences. This crucial issue was added to the goals in the present dissertation.

Dissertation Goal 3

In the second experimental part, we will investigate the relation that exists between non-adjacent phonological acquisitions during the first year of life and later word learning during the second year of life.

Summary of infants' phonotactic acquisition.



2-month-olds

- Show an early sensitivity to syllabic structure (Bertoncini & Mehler, 1981)

9-to-10-month-olds

- Are sensitive to the legality of adjacent phonotactic sequences of their native language (Jusczyk et al., 1993; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002)
- Are sensitive to the relative frequency in which adjacent phonotactic sequences occur in their native language (Jusczyk et al., 1994)
- Seem to be sensitive to the relative frequency of non-adjacent phonotactic sequences (Nazzi et al. 2009)
- Use adjacent phonotactic regularities to segment speech (Mattys & Jusczyk, 2001a)

17- to 20-month-olds

- Can learn word-object pairings if words are phonotactically legal, but fail to learn phonotactically illegal words (Graf Estes, Edwards & Saffran, 2011)

Figure 2. Brief summary of some important findings on infants' phonotactic acquisition.

Structure and aims of this dissertation

Taking as a point of departure what is known of infant phonotactic acquisition as described above, this dissertation explores infant language acquisition, focusing on the capacity that infants have to learn and use non-adjacent phonotactic patterns in their native language. The present dissertation is organized into two main experimental parts:

The first experimental part presents a set of studies exploring infants' sensitivity to non-adjacent phonological dependencies, analyzing the kind of statistical analyses that infants compute to acquire such dependencies, and the mechanisms underlying such acquisitions. The main questions addressed in this part are:

1.1- *Infants' ability to compute non-adjacent phonological dependencies*: Are infants sensitive to non-adjacent phonological dependencies? If so, when in development do these sensitivity emerge?

1.2- *Level of acquisition of the phonological dependencies*: At which level are non-adjacent phonological acquisitions acquired?

1.3- *Role of maturation on the acquisition of phonological dependencies*: What is the role of maturation in the acquisition of phonological dependencies? Are preterm infants sensitive to non-adjacent phonological dependencies? Is there a delay on preterm infants' phonological development?

1.4- *Role of the input on the acquisition of phonological dependencies*: How does the linguistic input influence phonological acquisitions? Is performance affected by acoustical differences in the stimuli used?

The second experimental part explores the existence of links between early speech perception and early lexical development at the level of word segmentation and word learning, mainly addressing the following questions:

2.1- *Phonotactical constrains in word segmentation*: Does prior phonotactic knowledge influence word segmentation?

2.2- *Relation between speech perception and word learning:* what relationship, if any, exists between prior phonotactic knowledge and word learning?

The presentation of these experimental results will be followed by a general discussion of the experimental evidence, synthesizing their contribution to our understanding of language acquisition and tracing perspectives for future research.

Part I

Experimental Work on speech Perception

1.1 Establishing the sensitivity to non-adjacent phonological dependencies

"Language is a process of free creation;
its laws and principles are fixed, but the manner
in which the principles of generation are used is free
and infinitely varied. Even the interpretation and use of
words involves a process of free creation."
Noam Chomsky

The first part of the experimental work in speech perception explores infants' sensitivity to non-adjacent phonological dependencies. Establishing such acquisitions is important since nonadjacent dependencies are a key feature of human languages. Moreover, because they involve learning properties between elements that are not contiguous in the signal, they might be more difficult to detect and thus to learn than adjacent dependencies, which had been the focus of prior research.

To explore infants' sensitivity to non-adjacent phonological dependencies we conducted three different experiments testing whether, and if when, French-learning infants present a preference for labial-coronal (LC) sequences that are more frequent in their native language compared to coronal-labial (CL) sequences. The results of these three experiments are crucial in the present dissertation, and they served as departure point of this work.

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Acquisition of Nonadjacent Phonological Dependencies in the Native Language During the First Year of Life

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Languages instantiate many different kinds of dependencies, some holding between adjacent elements and others holding between nonadjacent elements. In the domain of phonology–phonotactics, sensitivity to adjacent dependencies has been found to appear between 6 and 10 months. However, no study has directly established the emergence of sensitivity to nonadjacent phonological dependencies in the native language. The present study focuses on the emergence of a perceptual Labial-Coronal (LC) bias, a dependency involving two nonadjacent consonants. First, Experiment 1 shows that a preference for monosyllabic consonant-vowel-consonant LC words over CL (Coronal-Labial) words emerges between 7 and 10 months in French-learning infants. Second, two experiments, presenting only the first or last two phonemes of the original stimuli, establish that the LC bias at 10 months cannot be explained by adjacent dependencies or by a preference for more frequent coronal consonants (Experiment 2a & b). At 7 months, by contrast, infants appear to react to the higher frequency of coronal consonants (Experiment 3a & b). The present study thus demonstrates that infants become sensitive to nonadjacent phonological dependencies between 7 and 10 months. It further establishes a change between these two ages from sensitivity to local properties to nonadjacent dependencies in the phonological domain.

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During the past decades, many studies have shown how infants' initial language-general abilities change into abilities that are attuned to the language they are acquiring. Within the phonological domain, these studies have established that infants start learning the prosodic (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993b; Höhle, Bijeljac-Babic, Herold, Weissenborn, & Nazzi, 2009; Jusczyk, Cutler, & Redanz, 1993a), phonetic (Werker & Tees, 1984; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992), and phonotactic (Jusczyk et al., 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002; Jusczyk, Luce, & Charles-Luce, 1994) properties of their native language before their first birthday. However, infants have to acquire different sorts of native phonological properties, as a consequence of the fact that regularities in their native language occur at different levels of organization. The present study will be to address the issue of the acquisition of nonadjacent phonological dependencies.

Several levels of phonological organization can be distinguished. First, languages instantiate frequency regularities, some sounds appearing more frequently than others, as illustrated by the fact that crosslinguistically coronal consonants (consonants articulated with the flexible front part of the tongue in the front of the mouth cavity, roughly on the hard palate, e.g., sounds like /t/, /d/, /n/…) are more frequent than dorsal consonants (consonants articulated with the mid body of the tongue in the region of the soft palate, e.g., sounds like /k/, /g/, /ng/…; Paradis & Prunet, 1991). Second, positional regularities, which refer to the fact that some sounds are more frequent in some positions than in others, can also be observed, such as the predominance of Coronal-initial over Labial-initial words in French (see below and Table 5; labial are consonants articulated with one or both lips, e.g., sounds like /b/, /p/, /f/…), or the predominance of stressed syllables in word-initial position in English (Cutler & Carter, 1987). Third, adjacent regularities are observed, which refer to dependencies between sounds that are adjacent in the speech signal, such as the fact that in a given language, some consonant clusters are allowed, but not others (for example, in English, the sound /θ/ at the beginning of a syllable can be followed by /r/ as in the word *thrill*, but not by /l/, /n/, or /m/).

Fourth, languages present many types of nonadjacent phonological dependencies. For instance, many languages such as Khalkha, Mongolian, Yaka, Finnish, Hungarian, and Turkish (Nguyen, Fagyal, & Cole, 2008; Goldsmith, 1985; Meyer, 2007) exhibit vowel harmony, in the sense that vowels separated by consonants necessarily share a given phonetic feature within words (Turkish, for example, presents front–back harmony, according to which words cannot contain both front and back vowels). Consonant harmony can also be found in some languages such as Navajo (Young & Morgan, 1987; McDonough, 2003), though this is less frequent crosslinguistically (with some languages in fact favoring consonant disharmony, Nespor, Pena, & Mehler, 2003). Moreover, in some languages such as Tagalog, words receive infixes, that is, sounds inserted within the word stem to mark tense or aspect. Also, in Semitic languages such as Hebrew and Arabic, families of words correspond to consonantal roots (for the most part), such as *k-t-b* for writing, and variations in vowel identity indicate lexical class, number, gender... (Ryding, 2005). Both phenomena break the adjacency of the lexical root information. Additionally, the acoustic properties of coda syllables have been shown to influence the production of onset syllables (Nguyen & Hawkins, 1999). Nonadjacent effects are also found in writing, affecting pronunciation as attested by the fact that the short versus long pronunciations of vowels depend on the presence of a silent «e» ending, as in CAP-CAPE for example (Stanback, 1992; Pacton & Perruchet, 2008; Perruchet, Tyler, Galland, & Peereman, 2004).

Considering these different levels of organization, previous studies on phonological acquisition have shown that infants start distinguishing between legal and illegal sequences of adjacent phonemes in their native language between 6 and 10 months of age (Jusczyk et al., 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002). Infants were also found to become sensitive to the overall frequency of some phonemes or the frequency with which the phonotactically legal adjacent sequences appear in words of their language between the same ages (Jusczyk et al., 1994). In all cases, infants start preferring the structures that are either legal or more frequent in their native language during the second half of the first year of life. However, all of these phonotactic findings can be accounted for by sensitivity to frequency–positional–adjacent properties.

At present, even though nonadjacent dependencies are a key feature of human languages, infants' sensitivity to such dependencies in their native language at the phonological level remains very little explored. One exception is a study showing that Turkish-learning infants are already sensitive to vowel harmony at 6 months and are able to use vowel harmony and word stress to find word boundaries in continuous speech by 9 months (Van Kampen, Parmaksiz, Van De Vijver, & Höhle, 2008). Additionally, it is known that these dependencies affect adult processing. Studies with adults have found that nonadjacent dependencies present in the native language affect online lexical processing and can help or hinder word recognition (Hawkins & Nguyen, 2004; Kager & Shatzman, 2007; Nguyen & Hawkins, 1999; Suomi, McQueen, & Cutler, 1997). Given these effects, the present study begins investigating the acquisition of nonadjacent dependencies in the phonological domain during infancy, exploring the possibility that such nonadjacent acquisitions might be more difficult than adjacent ones because they involve elements not contiguous in the signal that might make them more difficult to detect and thus learn than adjacent dependencies.

This possibility is suggested by artificial language experiments in the domain of lexical and syntactic processing. These studies first established that while adults can use dependencies to learn words and rules from speech streams of new, artificial languages, the ease of such learning depends on adjacency: It is quick and easy when based on consistent relationships among temporally adjacent speech sounds or musical tones, but it is more difficult, and it appears possible only under specific circumstances, when based on nonadjacent speech sounds or musical tones (Aslin, Saffran, & Newport, 1998; Bonatti, Peña, Nespor, & Mehler, 2005; Creel, Newport, & Aslin, 2004; Onnis, Monaghan, Richmond, & Carter, 2005; Saffran, Aslin, & Newport, 1996). Moreover, learning of nonadjacent dependencies in an artificial language also appears to be dependent on whether natural languages commonly instantiate such nonadjacent dependencies (dependencies between syllables are more difficult to learn than dependencies between phonemes, Newport & Aslin, 2004; dependencies between consonants are easier to learn than dependencies between vowels, Bonatti et al., 2005).

Second, the hypothesis of increased difficulty at learning nonadjacent phonological dependencies is also based on artificial language studies on infants' acquisition of morphosyntactic and syntactic properties.[1] These studies using artificial languages in which variability was fully controlled tested the feasibility of infants' online learning of new adjacent or nonadjacent syntactic regularities. They established that while 12-month-olds can learn adjacent dependencies (e.g., Saffran & Wilson, 2003), they fail to learn nonadjacent dependencies at 12 months, but do so by 15 and 18 months (Gomez & Gerken, 1999; Gomez & Maye, 2005). Gomez and Maye (2005) further showed that learning nonadjacent dependencies is facilitated by increased variability of the elements intervening between the two nonadjacent dependents, and that such learning improves with age. These studies thus support the notion that new nonadjacent syntactic dependencies are more difficult to learn than adjacent ones. The present study will explore similar issues, but will differ from these previous studies in important ways.

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[1] Examples of infants' acquisition of morphosyntactic nonadjacent dependencies in the native language include the acquisition of subject–verb agreement (Farkas, 2009; Gomez, 2002; Legendre, Barriere, Goyet, & Nazzi, 2010; Soderstrom, White, Conwell, & Morgan, 2007; Nazzi, Barriere, Goyet, Kresh, & Legendre, 2011) and agreement between auxiliaries and inflectional morphemes (Santelmann & Jusczyk, 1998; Höhle, Schmitz, Santelmann, & Weissenborn, 2006). An example of the acquisition of syntactic nonadjacent dependencies in the native language is the acquisition of word order (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987). Note that these studies on natural languages, though informative, do not explore timing differences in the acquisition of adjacent versus nonadjacent dependencies.

First, it will focus on infants' acquisition of nonadjacent properties in the phonological (phonotactic) domain. Second, it will focus on the acquisition of nonadjacent phonological dependencies in the native language (with all the variability that characterizes natural languages). Hence, we will focus on infants' phonological acquisitions outside the laboratory, prior to the experimental session, rather than on their ability to learn new dependencies in the laboratory.

At present, only one previous study raised the issue of whether and when infants might start learning nonadjacent phonological dependencies in addition to adjacent ones in their native language (Nazzi, Bertoncini, & Bijeljac-Babic, 2009a). In that perception study, the dependencies investigated involved the distinction between Labial-Coronal (LC) words such as "beta" (that is, words starting with a labial consonant followed by a coronal consonant) and Coronal-Labial (CL) words such as "tuba" (that is, words starting with a coronal consonant followed by a labial consonant). The difference between the two types of words is usually thought of as a nonadjacent relation between two consonants separated by a vowel.[2] In French, the language of the infants tested, LC words are more frequent than CL words (cf Table 1). However, although this pattern is very frequent crosslinguistically, it does not seem to be universal. Indeed, one study presented evidence from 10 languages showing LC biases at the lexical level in all languages except Japanese and Swahili (MacNeilage, Davis, Kinney, & Matyear, 1999), thus raising acquisition issues. In previous research (only conducted on languages with LC biases at the lexical level), LC biases have been reported in early word production studies, and these biases have been interpreted in terms of production constraints according to which producing an LC sequence required less and easier movements than producing a CL sequence (Ingram, 1974; MacNeilage & Davis, 2000). In the perception

TABLE 1

Cumulative Frequency of LC and CL French Words (All Words versus $Cons_1Vow_1Cons_2$ Words Only) According to the Adult Database *Lexique 3* (New et al., 2001)

	All words	*$Cons_1Vow_1Cons_2$ words only*
Lab-Cor	71,822	6808
Cor-Lab	42,772	1179

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[2] Although some linguistic theories postulate independent consonantal and vocalic tiers of representations on which these consonants would be adjacent (cf, McCarthy, 1982; Kenstowicz, 1994), consonants would remain nonadjacent in terms of sound sequence, the level we are interested in here.

study by Nazzi et al. (2009a), the words tested were bisyllabic with a Cons$_1$Vow$_1$Cons$_2$Voy$_2$ structure (Cons for Consonant, Vow for Vowel), in which the consonants were either the labial consonants /p/ and /b/ or the coronal consonants /t/ and /d/. Infants started preferring the LC words between 6 and 10 months. These results were interpreted as evidence that, at a perceptual (rather than production) level, infants have become sensitive to these nonadjacent relations by 10 months.

However, two features of that study prevent us from making strong conclusions about the acquisition of nonadjacent dependencies. First, because bisyllabic stimuli were used, the LC bias found in that study could result from acquisition of dependencies between the two adjacent syllables. Second, a closer analysis of the stimuli used in Nazzi et al. (2009a) showed that there were differences between the two lists of words not only in global frequency of LC and CL words (the LC bias illustrated in Table 1), but also in terms of adjacent dependencies, some of which being higher for the LC words (marginal difference for Vow$_1$Cons$_2$ and significant difference for Cons$_2$Vow$_2$, cf Table 2).

Given the above comments, the question of infant acquisition of nonadjacent phonological properties is directly readdressed in the present study. Accordingly, Experiment 1 tested the emergence of an LC bias in French-learning infants between 7 and 10 months of age. Crucially though, the LC and CL stimuli used in Experiment 1 were chosen to be monosyllabic Cons$_1$Vow$_1$Cons$_2$ items to avoid the possible interpretation of an LC bias in terms of adjacent syllables. Moreover, the vowels used to make the stimuli in Experiment 1 were chosen so that the adjacent frequencies of Cons$_1$Vow$_1$Cons$_2$, Cons$_1$Vow$_1$ and Vow$_1$Cons$_2$ were matched across the LC and CL lists (cf Table 3) according to the Lexique 3 French database (New, Pallier, Ferrand, & Matos, 2001), to prevent a possible interpretation in terms of differences in the frequencies of adjacent phonemes. French-learning infants were tested at 7 and 10 months.

TABLE 2

Mean Frequency (and SDs) Associated with the Stimuli used in Nazzi et al. (2009a), for the Words Themselves, and their Constituting Diphones, Triphones, and 4-Phone Sequences

Bisyllabic Cons$_1$Vow$_1$Cons$_2$Vow$_2$ words

Word	*Cons$_1$ Vow$_1$*	*Vow$_1$ Cons$_2$*†	*Cons$_2$ Vow$_2$**	*Cons$_1$ Vow$_1$ Cons$_2$*	*Vow$_1$ Cons$_2$ Vow$_2$*	*Cons$_1$ Vow$_1$ Cons$_2$ Vow$_2$*
LC 12.6 (25)	6515 (9060)	4718 (3880)	7788 (6542)	305 (342)	311 (420)	22 (28)
CL 36.1 (57)	7310 (4580)	2434 (2098)	2534 (1108)	358 (387)	227 (191)	93 (150)

$^{\dagger}p < .10$; * < .05.

TABLE 3
Mean Frequency (and SDs) Associated with the Stimuli used in Experiment 1, for the Words Themselves, and their Constituting Diphone and Triphone Sequences

Experiment 1 – monosyllabic $Cons_1Vow_1Cons_2$ *words*

	Word	$Cons_1Vow_1$	Vow_1Cons_2	$Cons_1Vow_1Cons_2$
Lab-Cor	7.9 (16)	4389 (3518)	3246 (2561)	201 (323)
Cor-Lab	8.5 (13)	4207 (5971)	3344 (2785)	205 (327)

EXPERIMENT 1

Method

Participants

Thirty-two infants from French-speaking families were tested: 16 7-month-olds (mean age = 7 months 9 days; range: 7 months 2 days–16 days; 7 girls, 9 boys) and 16 10-month-olds (mean age = 10 months 7 days; range: 10 months 2 days–17 days; seven girls, nine boys). The data of two additional 7-month-olds were not included in the analyses because of fussiness–crying (*n* = 1) or for having a trial with two consecutive orientation times (original presentation + repetition) shorter than 1.5 sec in the test phase (*n* = 1). This last criterion was used to ensure that infants heard at least one or two words of each list. The data of one additional 10-month-olds were not included in the analysis because of fussiness–crying (*n* = 1).

Stimuli

Twenty-four monosyllabic $\mathrm{Cons}_1\mathrm{Vow}_1\mathrm{Cons}_2$ items were selected, combining labial consonants p and b, and coronal consonants t and d: Twelve items with a labial-coronal (LC) structure (3 bVd: /bɔ̃d/, */byd/, */bad/; 3 pVt: /pɔt/, /pɛ̃t/, */pot/; 3 bVt: /bɔt/, /byt/, /bat/; and 3 pVd: /pad/, */pod/, */pɑd/) and twelve items with a coronal-labial (CL) structure (3 dVb: */dɑ̃b/, /dob/, */dab/; 3 tVp: /tɑ̃p/, /tap/, /top/; 3 tVb: /tyb/, /tɔ̃b/, */tab/; and 3 dVp: */dap/, */dɛ̃p/, /dɔp/). Items in both lists were made up of exactly the same consonants, and the vowels were almost completely balanced across lists. Vowels were chosen to obtain balanced adjacent dependencies between the LC and CL lists for the $\mathrm{Cons}_1\mathrm{Vow}_1$, $\mathrm{Vow}_1\mathrm{Cons}_2$ and $\mathrm{Cons}_1\mathrm{Vow}_1\mathrm{Cons}_2$ sequences of phonemes according to the Lexique 3 database (cf Table 3). Because of this constraint on adjacent frequencies, we had to use a mix of both low frequency French words (*n* = 7) and pseudo-words legal in French ($n = 5$, marked by * in the lists given above) for both the LC and the CL lists.

The stimuli were recorded in a sound-attenuated booth by a French female native speaker who was naive to the hypotheses of the study. Two tokens of each item were selected. Four lists were created: Two lists with the twelve LC items (using different tokens of each item in the two lists, and reversing the order of the items in the two lists) and two lists with the twelve CL items (same manipulation). Overall, the LC and CL tokens did not differ in terms of duration, amplitude, and pitch characteristics (cf Table 4). The duration of all the lists was 18.00 sec (ISIs thus being in the range of 1030 ms).

Babbling questionnaire

Parents filled out a questionnaire, adapted from Stoel-Gammon (1989) babbling classification, to address questions regarding the perceptual–production nature of the LC bias. This questionnaire distinguishes three babbling levels:

1. Level 1: Utterances composed of a vowel, a syllabic consonant, a consonant-vowel, or vowel-consonant sequence in which the consonant is a glide or glottal, or any combination of the above (i.e., /a/, /m/, /wawə/).
2. Level 2: Utterances containing at least one consonant-vowel or vowel-consonant sequence in which the consonant is a true consonant not a glottal or glide one. The utterance could have more than one consonant or vowel, but the consonants would have to share the

TABLE 4
Acoustic Characteristics of the stimuli in Experiment 1, Experiment 2a/3a, and Experiment 2b/3b (Mean Values and SDs in Parenthesis)

	Duration (ms)	*RMS (dB)*	*Vowel pitch (Hz)*
Exp 1			
LC	564 (68)	42.77 (3.06)	231 (13)
CL	553 (55)	42.42 (3.38)	225 (11)
Exp 2a/3a			
L-Vow	447 (6)	42.76 (2.10)	220 (22)
C-Vow	446 (13)	45.21 (1.80)	223 (21)
Exp 2b/3b			
Vow-C	526 (12)	44.43 (2.28)	232 (20)
Vow-L	528 (9)	44.58 (2.29)	227 (16)

same place and manner of articulation (i.e., /ga/, /dɪdə/, /aba/, /baba/, /mɛmɛ/).

3. Level 3: Utterances containing at least two true consonants differing in place or manner of articulation (i.e., /gabɛ/, /ədæp/, /batɛ/). It is only at this level that infants are able to produce LC or CL sequences.

Procedure and apparatus

The experiment was conducted inside a sound-proof room, in a three-sided test booth made of pegboard panels (bottom part) and a white curtain (top part). The test booth had a red light and a loudspeaker (SONY xs-F1722) mounted at eye level on each of the side panels and a green light mounted on the center panel. Directly below the center light, a 5-cm hole accommodated the lens of a video camera used to monitor infants' behavior.

A PC computer terminal (Dell Optiplex computer), a TV screen connected to the camera, and a response box were located outside the sound-proof room. The response box, which was connected to the computer, was equipped with a series of buttons. The box was controlled by the observer, who looked at the video of the infant on the TV screen and pressed the buttons of the response box according to the direction the infant's head, thus starting and stopping the flashing of the lights and the presentation of the sounds. Both the observer and the infant's caregiver wore earplugs and listened to masking music over tight-fitting closed headphones, which prevented them from hearing the stimuli presented. Information about the direction and duration of the head-turn and the total trial duration were stored in a data file on the computer.

The classic version of the head-turn preference procedure (HPP) was used in the present study (cf Jusczyk et al., 1993a). Each infant was held on a caregiver's lap. The caregiver was seated in a chair in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented in that direction. Then, the center light was extinguished, and the red light above the loudspeaker on one of the side panels began to flash. When the infant made a turn of at least 30° in the direction of the loudspeaker, the stimulus for that trial began to play. The stimuli, stored in digitized form on the computer, were delivered by the loudspeakers via an audio amplifier (Marantz PM4000). Each stimulus was played to completion (i.e., when all the words of the list had been presented) or stopped immediately after the infant failed to maintain the 30° head-turn for two consecutive seconds (200 ms fade-out). If the infant turned away from the target by 30° in any direction for <2 sec and then turned back again, the trial continued but the time spent looking away was not included in the orientation time. Thus, the maximum orientation time for a given trial was the duration of the entire speech sample. If a trial was < 1.5 sec, the trial was repeated, and the original orientation time was discarded. The flashing red light remained on for the entire duration of the trial.

Each experimental session began with two musical trials, one on each side (randomly ordered) to give infants an opportunity to practice one head-turn to each side before the test session itself. The test phase consisted of two test blocks (both lists of both structures being presented in each block, hence leading to eight test trials). The order of the different lists within each block was randomized.

Results and discussion

Mean orientation times to the LC and CL lists were calculated for each infant. The data for the 7-month-olds ($M_{LC} = 10.15$ sec, SD = 2.34 sec; $M_{CL} = 9.67$ sec, SD = 3.24), and for the 10-month-olds ($M_{LC} = 10.41$ sec, SD = 2.80 sec; $M_{CL} = 7.64$ sec, SD = 2.00 sec), are presented in Figure 1. A two-way ANOVA with the between-subject factor of age (seven versus 10 months) and the within-subject factor of lexical structure (LC versus CL words) was conducted. The effect of lexical structure was significant, $F(1, 30) = 7.19$, $p = .01$, $\eta p^2 = .19$, infants having longer orientation times to LC than to CL lists. The effect of age was not significant, $F(1, 30) = 1.55$, $p = .22$. However, the interaction between age and lexical structure approached significance, $F(1, 30) = 3.54$, $p = .07$, $\eta p^2 = .11$ indicating that the effect of lexical structure changed with age. Planned comparisons showed that the lexical structure effect was not significant at 7 months, $F(1, 30) = 0.32$, $p = .57$, but was significant at 10 months, $F(1, 30) = 10.41$, $p < .001$, $d = 1.14$. A bias for LC stimuli was found in only nine of the 16 7-month-olds ($p = .40$, binomial test), but in 15 of the 16 10-month-olds ($p < .001$, binomial test).

The results of the babbling questionnaire established that all but one 7-month-old and all 10-month-olds were at babbling level 2, the remaining 7-month-old being at babbling level 1. None of the infants produced sequences with varied consonants (babbling level 3), thus none produced the kinds of LC and CL structures used in our experiment.

Experiment 1 establishes the emergence of a perceptual labial-coronal (LC) bias between the ages of 7 and 10 months for monosyllabic $Cons_1Vow_1Cons_2$ items, extending the developmental pattern previously found for bisyllabic $Cons_1Vow_1Cons_2Vow_2$ words (Nazzi et al., 2009a). More importantly, given that the present stimuli were $Cons_1Vow_1Cons_2$ items, and given that adjacent dependencies were controlled (that is, the

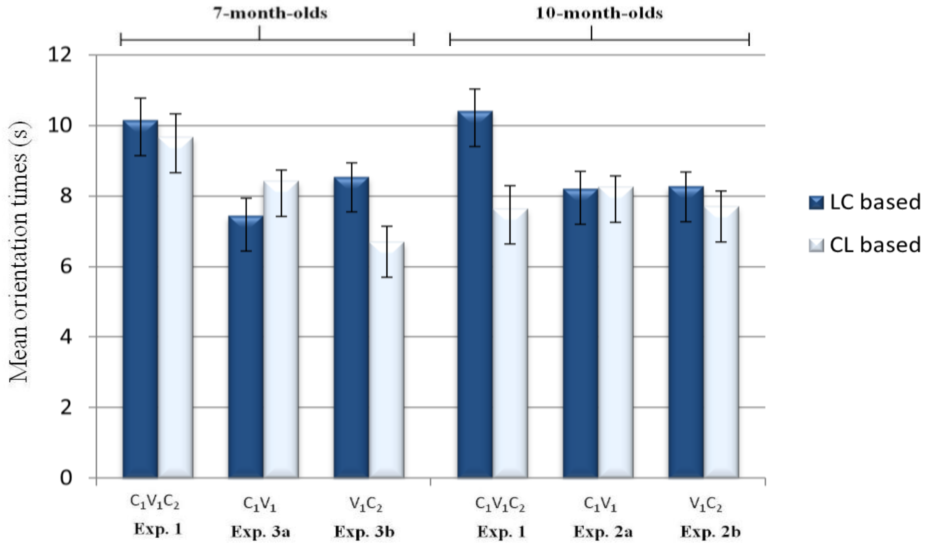

Figure 1 Mean orientation times (and SE of the mean) to the LC and CL stimuli in Experiment 1, to the L-initial versus C-initial items in Experiment 2a and 3a and to the L-final versus C-final items of Experiment 2b and 3b. Left panel: 7-month-old infants; Right panel: 10-month-old infants.

$\text{Cons}_1\text{Vow}_1$ and the $\text{Vow}_1\text{Cons}_2$ were chosen so that there was no significant difference between the adjacent sequences of the LC and CL lists according to the Lexique 3 database), these results support the interpretation that by 10 months, infants have learned some nonadjacent dependencies present in the French lexicon, more specifically, the general predominance of nonadjacent sequences of LC consonants over CL consonants in French words.

However, because there is no frequency database for infant-directed speech, the adjacent frequency controls made in preparation of the stimuli of Experiment 1 were based on an adult database, with no full guarantee that the frequencies would be exactly the same in both types of input. To further differentiate the relative contribution of the nonadjacent relationship between the two consonants and the adjacent relationships, two additional control experiments were run at both 7 and 10 months. For these control experiments, the stimuli of Experiment 1 were rerecorded, removing either the final consonant (leaving L-initial and C-initial $\text{Cons}_1\text{Vow}_1$ items) or the initial consonant (leaving C-final and L-final $\text{Vow}_1\text{Cons}_2$ items). This manipulation removed the nonadjacent dependency we are investigating, while adjacent dependencies between the two lists of stimuli remained identical to those in Experiment 1. These control experiments were first run with 10-month-olds (Experiments 2a and b). If 10-month-old infants were sensitive to nonadjacent dependencies in Experiment 1, they should have no preference in either of these two additional conditions. By contrast, if they were reacting to differences in adjacent frequencies (present in the infants' input, but not in the adult lexicon), then they should prefer L-initial over C-initial $\text{Cons}_1\text{Vow}_1$ items in Experiment 2a, or C-final over L-final Vow_1-Cons_2 items in Experiment 2b, or both.

These control experiments further tested possible frequency or positional effects that might have affected the 10-month-old's preferences. Indeed, different analyses of the French lexicon were conducted in Lexique 3. Overall, coronal consonants were much more frequent than labial consonants (frequency of 3,273,410 for five labials versus 5,971,259 for eight coronals). Moreover, we found a predominance of C-initial words over L-initial words, and a predominance of C-final words over L-final words (cf Table 5). If infants were sensitive to these frequency–positional factors, they should prefer C-initial words in Experiment 2a (a frequency bias that would go against the observed preference for LC words), and C-final words in Experiment 2b (a frequency bias that would support a preference for LC words). Note that these frequency–positional predictions differ from the potential adjacent dependency predictions, and only one of them would support the observed LC bias at 10 months.

Additionally, we ran some further corpus analyzes to test that the LC effect truly reflects a nonadjacent regularity, rather than being the result of combined biases for L-initial and C-final words. To do so, we extracted from Lexique all $\text{Cons}_1\text{Vow}_1\text{Cons}_2$ monosyllables (corresponding to the structures that were used as stimuli in Experiment 1) beginning and ending with Labial or Coronal consonants. The results for the token analysis are presented in Table 6. The numbers of tokens of LC, CL, LL, and CC $\text{Cons}_1\text{Vow}_1\text{Cons}_2$ monosyllables observed in the French adult database Lexique 3 are presented in the left panel. Additionally, the numbers of tokens of LC, CL, LL, and CC $\text{Cons}_1\text{Vow}_1\text{Cons}_2$ monosyllables predicted if L and C onsets and codas combined in an independent (rather than dependent) way are presented in the right panel. A chi^2 test established that the two distributions were different, chi^2 (ddl = 1) = 37.18, $p < .001$. The same results are found when counting types rather than tokens. This finding provides evidence that the LC sequences occur more often than would be predicted based on the number of occurrences of L and C consonants, and their separate tendencies to occur in onset or coda positions.

TABLE 5
Cumulative Frequency of L-Initial versus C-Initial, and L-Final versus C-Final Words According to the French Adult Database Lexique 3

	Word onset		*Word coda*	
	Monosyllables	*All words*	*Monosyllables*	*All words*
Labial	37,140	187,137	1745	19,272
Coronal	165,813	306,040	44,359	125,184

TABLE 6
Total Number of Tokens of LC, CL, LL, and CC Cons$_1$Vow$_1$Cons$_2$ Monosyllables Observed in the French Adult Database Lexique 3 (Left Panel), versus Predicted by Independent Combination of L and C in Onsets and Codas (Right Panel)

	Observed		*Predicted if independent*	
2nd Cons	*Labial*	*Coronal*	*Labial*	*Coronal*
1st Cons				
Labial	158	904	218	844
Coronal	340	1022	280	1082

To explore alternatives to the nonadjacent dependency interpretation of the Labial-Coronal bias found in Experiment 1 at 10 months (namely, adjacent effects because of different properties of the input to infants, or frequency–positional effects), two new groups of 10-month-olds were tested on either L-Vow versus C-Vow stimuli (Experiment 2a), or Vow-C versus Vow-L stimuli (Experiment 2b). Note that both L-Vow and Vow-C stimuli are structures in line with the Labial-Coronal sequence (which we will call LC-based structures), while both C-Vow and Vow-L stimuli are structures in line with the Coronal-Labial sequence (which we will call CL-based structures).

EXPERIMENTS 2A & B

Method

Participants

Sixteen 10-month-old infants from French-speaking families were tested for each experiment (Experiment 2a: Mean age = 10 months 9 days; range: 10 months 2 days–22 days; five girls, 11 boys; Experiment 2b: Mean age = 10 months 13 days; range: 10 months 4 days–22 days; nine girls, seven boys). The data of one additional infant for each experiment were not included in the analysis because of fussiness–crying.

Stimuli experiment 2a

The final consonants of the 24 Cons$_1$Vow$_1$Cons$_2$ words of Experiment 1 were removed to obtain L-initial and C-initial Cons$_1$Vow$_1$ sequences. Because of a couple of repetitions of the sequences obtained, the final list contained ten sequences with a labial-vowel (L-initial) structure (five b-initial: /bɔ̃/, /by/,/ba/,/bɔ/,/bɑ̃/; five p-initial: /pɔ/, /pɛ̃/, /po/, /pa/, /pɑ̃/), and 10 items with a coronal-vowel (C-initial) structure (five d-initial: /dɑ̃/, /do/, /da/, /dɔ/, /dɛ̃/; five t-initial: /tɑ̃/, /ta/, /to/, /ty/, /tɔ̃/). Vowels were almost completely balanced across lists, and adjacent dependencies were fully balanced across lists (see Table 3). These two-phoneme sequences were recorded in a sound-attenuated booth by the same French female native speaker as Experiment 1, naive to the hypotheses of the study. Two tokens of each word were selected. Four lists were made up: Two lists with the ten L-initial words (using different tokens of each item in the two lists, and reversing the order of the items in the two lists) and two lists with the ten C-initial words (same manipulation). Overall, the L-initial and C-initial tokens did not differ in terms of duration, amplitude, and pitch characteristics (cf Table 4). The duration of all the lists was 14.00 sec (ISIs being in the range of 1050 ms).

Stimuli experiment 2b

The initial consonants of the 24 $Cons_1Vow_1Cons_2$ words of Experiment 1 were removed to obtain C-final and L-final Vow_1Cons_2 sequences. Because of a couple of repetitions of the sequences obtained, the final list contained ten sequences with a vowel-coronal (C-final) structure (five d-final: /ɔ̃d/, /yd/, /ad/, /od/, /ɑ̃d/; five t-final: /ɔt/, /yt/, /ɛ̃t/, /ot/, /at/) and ten items with a vowel-labial (L-final) structure (five b-final: /yb/, /ɔ̃b/, /ɑ̃b/, /ob/, /ab/; five p-final: /ɑ̃p/, /ap/, /op/, /ɔp/, /ɛ̃p/); Again, vowels were almost completely balanced across lists, and adjacent dependencies were fully balanced across lists. These two-phoneme sequences were recorded in a sound-attenuated booth by the same French female native speaker as Experiment 1, naive to the hypotheses of the study. Two tokens of each word were selected. Four lists were made up: Two lists with the ten C-final words (using different tokens of each item in the two lists, and reversing the order of the items in the two lists) and two lists with the ten L-final words (same manipulation). Overall, the C-final and L-final tokens did not differ in terms of duration, amplitude, and pitch characteristics (cf Table 4). The duration of all the lists was 14.00 sec (ISIs being in the range of 970 ms).

Babbling questionnaire

The babbling questionnaire was again collected for all the infants.

Procedure and apparatus

The procedure and apparatus were the same as in Experiment 1.

Results and discussion

Mean orientation times to the L-Vow and C-Vow lists of Experiment 2a were calculated for each infant and are presented in Figure 1. Mean orientation times were 8.20 sec (SD = 2.19 sec) for the L-Vow list and 8.25 sec (SD = 2.10) for the C-Vow list. Similarly, mean orientation times to the Vow-C and the Vow-L lists of Experiment 2b were calculated for each infant and are presented in Figure 1. Mean orientation times were 8.27 sec (SD = 1.56 sec) for the Vow-C list and 7.69 sec (SD = 1.57) for the Vow-L list.

A two-way ANOVA with the between-subject factor of Experiment (2a versus 2b) and the within-subject factor of lexical structure (LC-based versus CL-based) was conducted. Both main effects were not significant ($F(1, 30) = .67$, $p = .41$, for lexical structure; $F(1, 30) = 0.16$, $p = .68$, for experiment). Additionally, the interaction between experiment and lexical structure was not significant, $F(1, 30) = .91$, $p = .34$. Planned comparisons showed that the lexical structure effect was not significant in either Experiment 2a, $F(1, 30) = .009$, $p = .92$ (a preference for L-Vow items was only found for eight of the 16 infants, $p = .60$, binomial test) or Experiment 2b, $F(1, 30) = 1.57$, $p = .21$ (a preference for Vow-C items was only found for nine of the 16 infants, $p = .40$, binomial test).

The absence of preference in the present control experiments establishes that 10-month-olds in Experiment 1 were not responding to adjacent properties (between $\text{Cons}_1\text{Vow}_1$ or $\text{Vow}_1\text{Cons}_2$) of the stimuli, because these adjacent properties were also present in Experiment 2a and 2b. This suggests that the frequency controls that we had made on the basis of the adult Lexique 3 database were appropriate for infant testing. More importantly, they establish that, in Experiment 1, infants were responding to nonadjacent properties, namely the predominance of LC words over CL words in the French lexicon.

Moreover, the results of the present control experiments did not reveal a preference for stimuli with Coronal consonants over stimuli with Labial consonants (no C-initial bias in Experiment 2a; no C-final bias in Experiment 2b), even though our analysis in Lexique 3 showed that C-initial and C-final words are more frequent than words starting or finishing with a labial consonant both in terms of cumulative frequency (cf Table 5) and in terms of total number of words in the French lexicon (cf Table 7). The fact that these differences were not mirrored in our data suggests that at 10 months, overall–positional phoneme frequencies do not influence infants' listening preferences. Could it be that younger infants are sensitive to these frequency differences? To explore such a possibility, which would suggest developmental changes, the two control studies were conducted at 7 months.

TABLE 7
Total Number of L-Initial versus C-Initial, and L-Final versus C-Final Words According to the French Adult Database Lexique 3

	Word onset		*Word coda*	
	Monosyllables	*All words*	*Monosyllables*	*All words*
Labial	144	13,405	32	2659
Coronal	222	13,358	89	11,072

Lastly, results of the babbling questionnaires showed that all infants were at babbling level 2 for both experiments (as also found for the 10-month-olds in Experiment 1), thus that none of the infants were producing LC and CL structures.

Taken together our results show that the LC preference found at 10 months of age in Experiment 1 cannot be accounted for by sensitivity to overall–positional phoneme frequencies, nor to L-initial or C-final biases. Additionally, 10-month-old infants did not show any preference for the C-initial sequences that are more frequent in French. Thus, 10-month-old infants' preference for LC sequences is likely to be the result of infants' prior acquisition of the input regularity that in French, their native language, the nonadjacent LC pattern is much more frequent than the CL pattern. To explore younger infants' potential sensitivity to overall–positional phoneme frequencies, the L-initial and C-final studies were conducted with two new groups of 7-month-old infants.

EXPERIMENTS 3A & B

Method

Participants

Sixteen 7-month-old infants from French-speaking families were tested for each experiment (Experiment 3a: Mean age = 7 months 9 days; range: 7 months 2 days–19 days; eight girls, eight boys; Experiment 3b: Mean age = 7 months 13 days; range: 7 months 2 days–22 days; 11 girls, five boys). The data of five additional 7-month-olds were not included in the analyses because of fussiness–crying (two for Experiment 3a, three for Experiment 3b).

Stimuli

The stimuli for Experiments 3a and 3b were the same as those used in Experiments 2a and 2b, respectively.

Babbling questionnaire

The babbling questionnaire was also collected for all the infants.

Procedure and apparatus

The procedure and apparatus were the same as in Experiment 1.

Results and discussion

Mean orientation times to the L-Vow and C-Vow lists of Experiment 3a were calculated for each infant and are presented in Figure 1. Mean orientation times were 7.44 sec (SD = 1.93 sec) for the L-Vow list and 8.42 sec (SD = 1.24) for the C-Vow list (Figure 1). Similarly, mean orientation times to the Vow-C and the Vow-L lists of Experiment 3b were calculated for each infant and are presented in Figure 1. Mean orientation times were 8.54 sec (SD = 2.03 sec) for the Vow-C list and 6.70 sec (SD = 2.21) for the Vow-L list.

A two-way ANOVA with the between-subject factor of Experiment (3a versus 3b) and the within-subject factor of lexical structure (LC-based versus CL-based) was conducted. Both main effects were not significant ($F(1, 30) = 1.77$, $p = .19$, for lexical structure; $F(1, 30) = 0.13$, $p = .71$, for experiment). However, the interaction between experiment and lexical structure was significant, $F(1, 30) = 19.65$, $p < .001$, $\eta_p^2 = .40$, because of the fact that infants preferred stimuli with coronal consonants over stimuli with labial consonants in both experiments. Planned comparisons showed that the lexical structure effect was significant in Experiment 3a, $F(1, 30) = 4.80$, $p = .03$, $d = -.60$, suggesting the existence of a C-initial bias (found for 12 of the 16 infants, $p = .03$, binomial test). The lexical structure effect was also significant in Experiment 3b, $F(1, 30) = 16.62$, $p < .001$, $d = .87$, supporting the existence of a C-final bias (found for 14 of the 16 infants, $p = .002$, binomial test). Thus, items with coronal consonants were favored over items with labial consonants, a pattern that is predicted by the higher frequency of coronals over labials in French words, overall, but also in word-initial and word-final positions (cf Table 5). Implications of these findings are further discussed in the general discussion.

Regarding the babbling questionnaire, seven infants were at level 1, and the remaining were infants at level 2. Thus, as also found for Experiments 1 and 2a & b, none of the infants were at level 3, thus none produced LC and CL structures.

Additionally, we compared all the results of Experiments 1, 2a & b, and 3a & b by conducting a three-way ANOVA with the between-subject factors of age (seven versus 10 months) and type of stimuli ($Cons_1Vow_1Cons_2$, $Cons_1Vow_1$ and Vow_1Cons_2), and the within-subject factor of lexical structure (LC-based versus CL-based). The effect of type of stimuli was significant, $F(2, 90) = 7.82$, $p = .001$, $\eta_p{}^2 = .15$, indicating that mean orientation times were longer for the $Cons_1Vow_1Cons_2$ stimuli, probably due to the fact that the $Cons_1Vow_1Cons_2$ lists had two more words (12 versus 10) and were therefore longer (18 versus 14 sec). The effect of lexical structure was also significant, $F(1, 90) = 9.32$, $p = .003$, $\eta_p{}^2 = .09$, indicating that infants preferred, overall, the LC-based structures. Importantly though, both the interaction between type of stimuli and lexical structure, $F(2, 90) = 6.68$, $p = .002$, $\eta_p{}^2 = .13$, and the interaction between age, type of stimuli, and lexical structure, $F(2, 90) = 4.10$, $p = .02$, $\eta_p{}^2 = .08$, were significant. This pattern of interaction is because of the fact that lexical structure was only significant at 10 months for $Cons_1Vow_1Cons_2$ stimuli (Experiment 1), and at 7 months for $Cons_1Vow_1$ and Vow_1Cons_2 stimuli (Experiment 3a & b). All other effects and interactions failed to reach significance.

GENERAL DISCUSSION

The goal of the present study was to explore the early acquisition of nonadjacent phonological properties of the native language. Accordingly, we investigated when French-learning infants develop a preference for $Cons_1Vow_1Cons_2$ items with a labial-coronal structure over $Cons_1Vow_1Cons_2$ items with a coronal-labial structure. It is important to emphasize that the labial-coronal structures are comparatively more frequent in French than coronal-labial ones, this LC bias being the result of a dependent relation between the two nonadjacent consonants (cf our analyses presented on Table 6). The results of Experiment 1 showed that this bias emerges between 7 and 10 months of age, a finding predicted by nonadjacent acquisition. This interpretation is reinforced by the way the stimuli were constructed, controlling for adjacent dependencies using the adult database Lexique 3.

However, as discussed earlier, two other effects could have affected the 10-month-olds' preferences. First, the adjacent frequency control could only be calculated on an adult database, because no suitable database is available for very young infants. If these frequencies were different for the infant input and were responsible for the observed labial-coronal preference at 10 months, then presenting 10-month-olds with $Cons_1Vow_1$ should result in a preference for labial-initial items and–or presenting them with Vow_1Cons_2 should result in a preference for coronal-final items. Second, frequency–positional effects might also have contributed to the labial-coronal preference, at least when it comes to final coronals, because coronals are overall more frequent than labials in French, and this is true both in word-initial and word-final position. If 10-month-olds were reacting to these frequency–positional properties, then presenting 10-month-olds with $Cons_1Vow_1$ should result in a preference for coronal-initial items (an effect that would go against a labial-coronal preference) and presenting them with Vow_1Cons_2 should result in a preference for coronal-final items (an effect that would support a labial-coronal preference). These effects were evaluated in two additional control experiments presenting infants with either the first two phonemes ($Cons_1Vow_1$, Experiment 2a) or the last two phonemes (Vow_1-$Cons_2$, Experiment 2b) of the original stimuli. The results of Experiments 2a-b rule out these alternative interpretations, because no preferences were obtained at 10 months. These results further support the conclusion that the control of adjacent dependencies, made on the adult database Lexique 3, is also appropriate for infant input.

Therefore, the present study provides new evidence suggesting that infants become sensitive to nonadjacent dependencies at the phonological level very early in development, that is, between 7 and 10 months of age. This is the same time period during which infants have been found to become sensitive to native phonotactic properties in previous studies (Jusczyk et al., 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002; Jusczyk et al., 1994; Nazzi et al., 2009a). However, our findings also bring new data regarding younger infants' sensitivity to native language properties, and new evidence supporting developmental changes between 7 and 10 months. At 7 months, infants failed to show any preference for LC or CL words. However, they were found to prefer C_1V_1 items starting with a coronal rather than a labial consonant (Experiment 3a) and V_1C_2 items ending with a coronal rather than a labial consonant (Experiment 3b). Both in Experiments 3a and 3b, they preferred to listen longer to stimuli including coronal rather than labial consonants, which might suggest the existence of a general coronal preference. Given that coronal consonants are more frequent in French overall, it is likely that the present results are because of 7-month-olds' sensitivity to frequency properties of their native language, although a positional interpretation in terms of coronals being more frequent in onsets and codas of words cannot be totally ruled out. In both cases, the effect would be because of local–frequency properties rather than based on nonadjacent dependencies. Note that these preferences appear to neutralize one another when $Cons_1Vow_1Cons_2$ words are presented at 7 months (Experiment 1).

The results for the younger French-learning infants suggest that they have learned by 7 months of age that coronals are more frequent in their native language than labials. These present findings, based on the observation of preferences for more frequent structures, might seem at odds with the literature on phoneme discrimination which, for the most part, does not report effects of consonant-based phonological acquisitions before 10 months of age (Werker & Tees, 1984; Best, McRoberts, & Sithole, 1988). However, they are in line with a recent study showing that consonant discrimination on the voicing continuum (də/tə contrast) becomes language specific between 4 and 8 months in French-learning infants (Hoonhorst et al., 2009). Provided that the two lines of research can be directly compared, then the apparent developmental advantage of French-learning infants over English-learning infants for phonological acquisition would need to be explained. This will require crosslinguistic research that would further evaluate whether there is really a phonological advantage in French, which might result from the fact that lexical prosody is less marked than in English or German, so that French-learning infants might devote more processing resources to phonological, compared to prosodic, processing than English- or German-learning infants. A first step would be to verify whether the present early coronal preference at 7 months is specific to learning French, or whether it is more general and can be found in other languages because coronals are very frequent in many languages including English and Spanish (Kenstowicz, 1994; Paradis & Prunet, 1991). A second step would be to verify that the coronal preference found at 7 months really reflects phonotactic acquisition and not a general early preference for coronal consonants, which could be carried out by testing even younger infants.

Testing English-learning infants on this issue would also be important, because our findings for 7-month-olds appear at odds with previous phonotactic findings in English showing that 10-, but not 6-month-olds, prefer more frequent items when contrasting legal items on the basis of their frequency (Jusczyk et al., 1994). Indeed, in that study, the contrasted stimuli differed not only by the fact that adjacent relationships were more frequent in one list than in the other, but also by the fact that one list contained some phonemes that had higher positional frequencies in the target language than the other list. This apparent difference in results in the younger infants will have to be further explored. If the present coronal preference could not be found in English 7-month-olds, then several other nonexclusive explanations could account for the difference in results. First, the infants in the present study were older by 1 month than those in Jusczyk et al. (1994). Second, the infants in both studies were learning different languages, which might yield slightly different developmental trajectories. Third, the effects found in the present study were obtained using stimuli made up of two rather than three phonemes, as in Jusczyk et al. (1994). Fourth, it is unclear whether total frequencies (and not just positional frequencies) of phonemes also varied in Jusczyk et al. (1994); if not, then the different outcome in the two studies might suggest that by 6/7 months, infants are sensitive to absolute phoneme frequencies rather than positional frequencies.

Taken together, our findings with 7- and 10-month-olds suggest developmental changes, infants moving from sensitivity to local–frequency properties to sensitivity to nonadjacent dependencies. Possibly, this switch from computing adjacent dependencies to computing nonadjacent dependencies as age and thus amount of input increases can be linked to changes in memory limitations. Such a switch is also reminiscent of the developmental changes found in studies on infants' learning of new nonadjacent syntactic dependencies in which infants appear to move from adjacent- to nonadjacent-based learning between 12 and 15 months of age (Gomez & Gerken, 1999; Gomez & Maye, 2005; Saffran & Wilson, 2003), a pattern of change in line with Newport's (1988) ''less is more'' hypothesis (cf Gomez & Maye, 2005; for a related discussion). According to Gomez and Maye (2005), this developmental change is because of learners focusing on local information when dependencies between adjacent elements are informative, that is under small set-size conditions, while focusing on nonadjacent structures under conditions of high variability, when conditional probabilities between adjacent elements are low, thus uninformative. However, learning of nonadjacent dependencies in an artificial language could be found even at 12 months if infants had first been familiarized with adjacent dependencies, suggesting that learning of adjacent dependencies might precede and facilitate learning of nonadjacent dependencies (Lany & Gomez, 2008). Similar mechanisms could explain the pattern of results observed in the present study, with the acquisition of local–adjacent phonological properties before that of nonadjacent ones, in a context of large variability of the intervening elements (here the vowel separating the two consonants). Accordingly, we would predict that while, in the laboratory, infants can be taught new adjacent phonotactic relations in an artificial language learning experiment by 4 months of age (Chambers, Onishi, & Fisher, 2003; Seidl, Cristià, Bernard, & Onishi, 2009), they should only become able to learn new nonadjacent relations in such learning experiments at a later age. However, the acquisitions in the phonological domain are found earlier in development than those in the morphosyntactic one. This is congruent with a recent study using optical topography which found that newborns appear to learn adjacent repetitions very rapidly, but not nonadjacent ones (Gervain, Macagno, Cogoi, Pena, & Mehler, 2008).[3]

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[3] Note that whether the ability to compute nonadjacent phonological dependencies emerges between 7 and 10 months, or whether both adjacent and nonadjacent dependencies can be computed at both ages and it is their respective weight that changes are two possible interpretations of the present pattern of results. Distinguishing these possibilities is beyond the scope of the present study and will have to be further investigated. The same issues are also valid for the studies on syntactic dependency acquisition discussed in the present paragraph.

Interestingly, the shift from local–frequency sensitivities to nonadjacent sensitivity might have functional implications for word learning. For example, while using information regarding the predominance of coronal consonants to segment the continuous speech stream would not provide a good segmentation cue (because of predominance of coronals both word initially and word finally, cf Table 5), the predominance of LC structures over CL structures could be the basis of an efficient segmentation procedure that would place word form boundaries before the occurrence of an LC sequence. If such a facilitative segmentation effect were found, it would generalize to nonadjacent dependencies effects of adjacent phonotactic regularities on word segmentation in 9-month-old infants (Mattys, Jusczyk, Luce, & Morgan, 1999; Mattys & Jusczyk, 2001) and adults (Mersad & Nazzi, 2011; Finn & Hudson Kam, 2008; Mattys, White, & Melhorn, 2005). Recent results support this possibility, showing that French-learning 10-month-olds are able to segment LC words, but not CL words (Nazzi & Gonzalez Gomez, 2011, January).

Such facilitative effects of the LC structure (but not of the predominance of coronals) might also translate at the level of new word learning. Although a recent study failed to find evidence of better learning of LC words over CL words in French-learning 20-month-olds (Nazzi & Bertoncini, 2009), it is possible that either the infants were too old to show such an effect or that the method used was not sensitive enough; further research should be conducted on this issue, in particular because another recent study found an advantage of learning phonotactically legal over illegal words in 17- to 20-month-old infants (Graf Estes, Edwards, & Saffran, 2011).

The present findings also have implications for our understanding of the nature of the labial-coronal effect. Classically, the effect has been interpreted as the result of production constraints (Ingram, 1974; MacNeilage & Davis, 2000). In contrast, Nazzi et al. (2009a) offered a perceptual interpretation of their finding of an LC preference in perception at 10 months, according to which 10-month-old infants would have acquired this input regularity of their native language (the fact that LC structures are more frequent than CL ones in French). This perceptual interpretation is reinforced by the results of Experiment 1 that extend the preference effect found at 10 months from bisyllabic to monosyllabic items, using more controlled stimuli. This interpretation is further confirmed by the results of the babbling questionnaire establishing that none of the 10-month-olds tested in the present study produced either LC or CL structures. Therefore, we propose that the labial-coronal bias involves both perceptual and production factors, because the labial-coronal bias found at 10 months is likely to reflect the perceptual acquisition of input regularities possibly reflecting articulatory constraints. One way to further explore the relationship between these perceptual and production effects would be to test infants growing up learning a language that does not show a labial-coronal advantage in the input and determine whether or not this affects the emergence of a perceptual bias around 10 months, and a production bias in the second year of life. Japanese would constitute such a language according to MacNeilage et al. (1999), and we have started analyzing the Japanese lexicon more thoroughly and testing Japanese adults (S. Tsuji, N. Gonzalez-Gomez, V. Medina, T. Nazzi & R. Mazuka, submitted) before starting testing Japanese-learning infants.

In conclusion, the present study provides new evidence that infants become sensitive to nonadjacent phonotactic dependencies in their native language at some point between 7 and 10 months of age. Furthermore, the present study is opening up several theoretical perspectives to be explored in the future. First, while the present study focuses on consonants, it will be important in the future to evaluate infant acquisition of nonadjacent vowel dependencies given that consonants and vowels appear to play different roles at different linguistic processing levels (Nespor et al., 2003; Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet, & Butler, 2009b). Second, the present study leaves open the question of the level at which the present nonadjacent acquisitions operate. According to an ‘‘item-based’’ hypothesis, infants would have learned that the phonemes ‘‘p’’ and ‘‘b’’ more often appear before the phonemes ‘‘t’’ and ‘‘d’’ than the other way round. According to an alternative ‘‘phonetic category’’ hypothesis, they would have generalized these acquisitions to a more abstract level and would have learned that when a labial and a coronal phoneme appear in a sequence, the labial phoneme is more likely to precede the coronal one. One way to distinguish the two hypotheses would be to test infants on pairs of labial and coronal phonemes that show a sequential effect opposite the overall labial-coronal effect. An analysis of Lexique 3 showed that out of 40 possible consonant pairs (five labials: /p/, /b/, /f/, /v/, /m/; eight coronals: /t/, /d/, /s/, /ʃ/, /z/, /ʒ/, /n/, /l/), five pairs (d-b, s-b, ʃ-f, s-v, and ʒ-b) had a reversed frequency bias, that is, more frequent coronal-labial than labial-coronal sequences. Future research will have to determine whether these specific pairs of phonemes give rise to a preference for coronal-labial sequences, as predicted by item-based learning, or to the opposite pattern as predicted by abstract learning, which will also provide information regarding the role of input in the emergence of the LC bias. Independently of what hypothesis turns out to be supported, it remains that nonadjacent phonological acquisition has started by 10 months of age.

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Are infants sensitive to non-adjacent phonological dependencies? If so when in development are they able to do it?

The results of the three experiments establish:

- The existence of the equivalent in early perception of the Labial-Coronal bias that was previously described in early production.
- Between 7 and 10 months of age infants start preferring LC structures over CL structures.
- 10-month-olds’ preference is due to the relative position of the non-adjacent consonants (all the adjacent frequencies were fully controlled).
- This preference is not due to adjacent dependencies, nor to L-initial or C-final biases.

→Therefore, we can conclude that 10-month-old infants are sensitive to non-adjacent phonological dependencies.

1.2 Exploring the level of generalization at which non-adjacent phonological dependencies operate

> *“A linguistic system is a series of*
> *differences of sound combined with a*
> *series of differences of ideas.”*
> *Ferdinand De Saussure*

Once we established that infants can learn non-adjacent phonological dependencies in their native language, the question about the limits or constraints that the computations that infants make, emerged immediately. This part of the dissertation is devoted to the exploration of the level of generalization at which non-adjacent phonological dependencies operate. To do so, we exploit the fact that the LC bias is not homogenously present in French lexicon, allowing us to analyze whether the perceptual labial-coronal bias found in French-learning 10-month-old infants applies:

a) To all sounds (corresponding to an overall LC bias in the French lexicon)
b) Differently to different manners of articulation (corresponding to an overall LC bias for plosive and nasal sequences versus a tendency for a CL bias for fricative sequences)
c) Differently to different pairs (corresponding to a CL bias for 5 pairs showing a CL advantage, and an LC bias for 35 pairs presenting a LC advantage).

All these possibilities were explored in a set of four different experiments that we present below.

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Phonological Feature Constraints on the Acquisition of Phonological Dependencies

Nayeli Gonzalez-Gomez[1] and Thierry Nazzi [1,2]

1. Introduction

During the complex process of learning a language infants have to be able to specify the properties of their native language. In this domain, a considerable amount of studies conducted during the past decades have shown that infants start specializing in the phonology of their native language during the second half on their first year of life. Infants start becoming sensitive to the prosodic characteristics of their native language by 6-9 months (Jusczyk et al., 1993a&b; Nazzi et al., 2000; Höhle et al., 2009), to its vocalic inventory by 6 months (Kuhl et al., 1992; Polka & Werker, 1994) and to the consonantal one some months later, by 6-10 months (Werker & Tees, 1984; Best et al., 1988; Hoonhorst et al., 2009). Furthermore, by 9/10 months of age, infants have started acquiring the phonotactic properties of their native language, showing a preference to listen to legal or high frequency phonotactic patterns in their language over illegal or low frequency ones (Jusczyk et al., 1993b, 1994). However, at present, the mechanisms and the level of generalization of these acquisitions remain largely unknown. The present research will focus on the acquisition of phonotactic properties, and aims at investigating the level at which these phonotactic acquisitions operate.

The Labial-Coronal bias was used to explore this question. This bias corresponds to the prevalence of sequences starting with a labial consonant followed by a coronal consonant, such as “pit” (LC pattern) over the opposite pattern, that is, sequences starting with a coronal consonant followed by a labial one, as in the word “tip” (CL pattern). This bias has first been found in early word production, when it was found that during the 50-word stage infants tend to produce more LC than CL sequences (Ingram, 1974; MacNeilage & Davis,

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2000). More recently, this bias has also been found at the perceptual level in two different studies. First Nazzi, Bijeljac-Babic and Bertoncini (2009) showed that between 6 and 10 months infants start preferring LC over CL sequences, the stimuli used in that study being bisyllabic Consonant-Vowel-Consonant-Vowel words. Second, Gonzalez-Gomez and Nazzi (2012) found that 10- but not 7-month-old infants listen longer to monosyllabic Consonant-Vowel-Consonant LC sequences than to equivalent CL sequences, thus extending the original finding by Nazzi et al. (2009). Control experiments by Gonzalez-Gomez and Nazzi (2012) further show that the bias is not due to a preference for L-initial sequences, or C-final ones, nor to adjacent properties of the stimuli (diphone frequencies). Rather, taken together, the results of both studies establish that this preference is based on a sensitivity to non-adjacent phonotactic properties, and probably arises from infants' acquisition of the fact that LC words are overall more frequent than CL words in their native language, French (as it is also in many other languages).

It could then be that, infants monitor the relative order of labial and coronal consonants in the input, like infants are sensitive to statistical information regarding the relative order of syllables in the input (for transitional probabilities, see Saffran et al., 1996, and Mersad & Nazzi, 2012, for data on French-learning infants), and learn by 10 months of age that their language contains more LC words than CL words. However, what are the constraints applying on these acquisitions? Interestingly, a detailed analysis of the French lexicon reveals that even if the LC bias is clearly present for sequences of plosive and nasal consonants, this is not the case for fricative sequences (c.f. Figure 1). Furthermore, if the statistical analysis focuses only on word-initial sequences an advantage for Coronal-Labial sequences is found for fricatives (c.f. Figure 2).

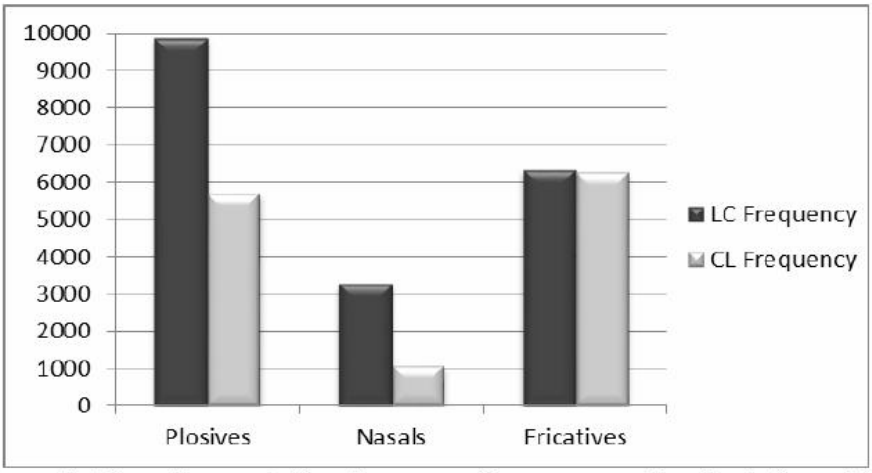

Figure 1. Overall cumulative frequency by manner of articulation of LC and CL French words according to the adult database *Lexique 3* (New, Pallier, Ferrand & Matos, 2001).

Accordingly, the differences that exist in the relative frequencies of LC and CL sequences depending on the kind of consonants, classified by manner of articulation, was exploited to investigate whether the LC bias operates, and thus is learned, at a global versus a more specific level, in this case at the level of phonetic categories determined by manner of articulation. Two hypotheses were evaluated. The first one states that the LC bias is learned at a global level, so that infants make statistical computations for all types of consonants taken together, resulting in the computation of a general LC and CL category, which should lead to an overall LC bias for their native language, French. Alternatively, these computations could be made at a more specific level, separately for consonants belonging to different consonant classes (here based on manner of articulation), and they might compute biases for each of these three subcategories; in this case, they should learn two LC biases (for plosives and nasals) and one CL bias (for fricatives).

The prior results by Nazzi et al. (2009) and Gonzalez-Gomez and Nazzi (2012) cannot tell apart these two hypotheses since both presented infants with stimuli made up exclusively of plosive consonants for which the LC bias found is predicted by both alternatives. Therefore, two experiments were conducted, with two groups of infants who were presented either with nasal consonants only (Experiment 1) or with fricative consonants only (Experiment 2). Their results will be compared with those obtained by Gonzalez-Gomez and Nazzi (2012) for plosive consonants only. According to the first hypothesis of an overall LC bias, an LC bias should be found for nasals but also, more importantly, for fricatives. On the other hand, according to the second hypothesis, an LC bias is predicted for nasals, but no effect or even an advantage for CL sequences is expected for fricatives.

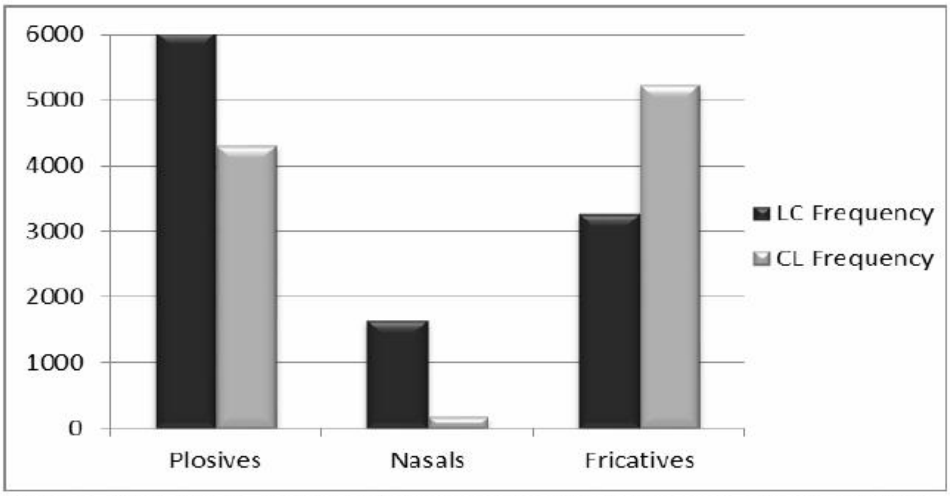

Figure 2. Word-initial cumulative frequency by manner of articulation of LC and CL French words according to the adult database *Lexique 3* (New, Pallier, Ferrand & Matos, 2001).

2. Experiment 1

2.1 Method

Participants. Sixteen 10-month-old infants from French-speaking families were tested (mean age = 10 months 12 days; range: 10 months 1 day – 10 months 21 days; 9 girls, 7 boys). The data of two additional infants were not included in the analyses due to fussiness/crying.

Stimuli. Twelve monosyllabic C_1VC_2 items were selected, combining the labial consonant “m” and the coronal consonant “n”. Only one pair of nasal consonants could be used, given that “m” is the only labial nasal and “n” is the only coronal nasal in French. There were 6 different items with a labial-coronal (LC) structure (mVn: /mɔn/, /mon/, /mun/, /man/, /myn/, /møn/) and 6 with a coronal-labial (CL) structure (nVm: /nɔm/, /nom/, /num/, /nam/, /nym/, /nøm/). Items in both lists were made up of exactly the same consonants and vowels. Vowels were chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the C_1V, VC_2 and C_1VC_2 sequences of phonemes according to the Lexique 3 database New et al., 2001).

The stimuli were recorded in a sound-attenuated booth by a French female native speaker who was naive to the hypotheses of the study. Two tokens of each item were selected. Two LC lists were created, one containing the first tokens of each LC items and the other the second tokens. Within each list, the 6 items were arranged in random order, and then repeated once in a different random order, leading to a list of 12 items.Two CL lists were constructed in the same way. The duration of all the lists was 18.00 s.

Procedure and Apparatus. The experiment was conducted inside a sound-proof room, in a three-sided test booth made of pegboard panels (bottom part) and a white curtain (top part). The test booth had a red light and a loudspeaker (SONY xs-F1722) mounted at eye level on each of the side panels and a green light mounted on the center panel. Directly below the center light a 5-cm hole accommodated the lens of a video camera used to monitor infants' behavior.

A PC computer terminal (Dell Optiplex computer), a TV screen connected to the camera, and a response box were located outside the sound-proof room. The response box, which was connected to the computer, was equipped with a series of buttons. The box was controlled by the observer, who looked at the video of the infant on the TV screen and pressed the buttons of the response box according to the direction the infant's head, thus starting and stopping the flashing of the lights and the presentation of the sounds. Both the observer and the infant's caregiver wore earplugs and listened to masking music over tight-fitting closed headphones, which prevented them from hearing the stimuli presented. Information about the direction and duration of the head-turn and the total trial duration were stored in a data file on the computer.

The classic version of the Head-turn Preference Procedure (HPP) was used in the present study (c.f. Jusczyk et al., 1993a). Each infant was held on a caregiver's lap. The caregiver was seated in a chair in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented in that direction. Then, the center light was extinguished and the red light above the loudspeaker on one of the side panels began to flash. When the infant made a turn of at least 30° in the direction of the loudspeaker, the stimulus for that trial began to play. The stimuli, stored in digitized form on the computer, were delivered by the loudspeakers via an audio amplifier (Marantz PM4000). Each stimulus was played to completion (i.e., when all the words of the list had been presented) or stopped immediately after the infant failed to maintain the 30° head-turn for 2 consecutive seconds (200 ms fade-out). If the infant turned away from the target by 30° in any direction for less than 2s and then turned back again, the trial continued but the time spent looking away was not included in the orientation time. Thus, the maximum orientation time for a given trial was the duration of the entire speech sample. If a trial was less than 1.5s, the trial was repeated and the original orientation time was discarded. The flashing red light remained on for the entire duration of the trial.

Each experimental session began with two musical trials, one on each side (randomly ordered) to give infants' an opportunity to practice one head-turn to each side before the test session itself. The test phase consisted of two test blocs (both lists of both structures being presented in each bloc, hence leading to 8 test trials). The order of the different lists within each bloc was randomized.

2.2 Results and Discussion

Mean orientation times to the LC and CL lists were calculated for each infant. The means for the group (M_{LC} = 8.75 s, SD = 1.80 s; M_{CL} = 7.33 s, SD = 1.70) are presented in Figure 3. A t-test revealed that the difference between the LC and CL trials was significant, $t_{(15)} = 2.43$, $p = .02$. This pattern was present in 13 of the 16 infants tested, a binomial test establishing that this pattern is significantly different from chance ($p = .011$).

Experiment 1 establishes that 10-month-old infants prefer the nasal LC sequences over the nasal CL sequences. These results establish the existence of an LC bias for nasal consonants, extending previous results showing a perceptual LC bias for plosive consonants (Nazzi et al., 2009; Gonzalez-Gomez & Nazzi, 2012). However, the present results do not allow us to choose from the two hypotheses that we discussed regarding the acquisition and scope of the LC bias (a general LC bias, versus biases for different phonetic categories defined by manner of articulation), given that there is also an LC bias for nasal consonants in the French lexicon. To further explore this question, a second experiment was conducted using fricative consonants. Fricatives are a crucial case to investigate this issue given that they do not follow the same pattern as plosives and nasals in the French lexicon: if anything, there are more fricative CL sequences than fricative LC sequences. Therefore, while the global bias hypothesis would still predict an LC bias for fricatives, the phonetic category hypothesis would predict no bias or a CL bias for this class of consonants.

3. Experiment 2

3.1 Method

Participants. Sixteen 10-month-old infants from French-speaking families were tested (mean age = 10 months 18 days; range: 10 months 4 day – 10 months 26 days; 9 girls, 7 boys). The data of three additional infants were not included in the analyses due to fussiness/crying.

Stimuli. Twenty-four monosyllabic C_1VC_2 items were selected, combining labial consonants "f" and "v", and coronal consonants "ʃ" and "s": twelve items with a labial-coronal (LC) structure (3 fVs: /fɔ̃s/, /fos/, /fɛ̃s/; 3 fVʃ: /fyʃ/, /faʃ/, /fɑ̃ʃ/; 3 vVs: /vɛ̃s/, /vɑ̃s/, /vos/; and 3 vVʃ: /vaʃ/, /vyʃ/, /vɔ̃ʃ/) and twelve items with a coronal-labial (CL) structure (3 ʃVf: /ʃɑ̃f/, /ʃof/, /ʃaf/; 3 ʃVv: /ʃɛ̃v/, /ʃav/, /ʃyv/; 3 sVf: /sɔ̃f/, /sof/, /sɛ̃f/; and 3 sVv: /syv/, /sɑ̃v/, /sɔ̃v/). Items in both lists were made up of exactly the same consonants and vowels, all vowels across the experiments being chosen in order to obtain balanced adjacent dependencies between the LC and CL lists. Two tokens of each item were recorded by the same speaker that recorded the stimuli for Experiment 1. Two LC lists and 2 CL lists, with a duration of 18.00 s, were constructed as in Experiment 1.

Procedure and Apparatus. Same as in Experiment 1.

3.2 Results and Discussion

Mean orientation times to the LC and CL lists were calculated for each infant. Means for the group (M_{LC} = 7.25s, SD = 1.72 s; M_{CL} = 8.89 s, SD = 2.38) are presented in Figure 3. A t-test revealed that the difference between LC and CL trials was significant, $t_{(15)} = 2.89$, $p = .01$. This pattern was present in 11 of the 16 infants tested ($p = .105$, binomial test).

A 2-way ANOVA was conducted to compare the results obtain by Gonzalez-Gomez and Nazzi (2012) for plosives, the results of Experiment 1 for nasals and the results of Experiment 2 for fricatives, taking the between-subject factor of manner of articulation (plosives versus nasals versus fricatives) and the within-subject factor of lexical structure (LC versus CL). The effect of lexical structure was significant, $F(1, 45) = 6.71$, $p = .01$, infants having generally longer orientation times to LC than to CL lists. The effect of manner of articulation was not significant, $F(2, 45) = 1.60$, $p = .21$. However, the interaction between manner of articulation and lexical structure was significant, $F(2, 45) = 15.79$, $p < .001$, indicating that the effect of lexical structure changed with manner of articulation. Planned comparisons showed that the difference between plosives and nasals was not significant, $F(1, 45) = 2.79$, $p = .12$, both showing an LC bias. However the differences between plosives and fricatives ($F(1, 45) = 30.06$, $p < .001$) and nasals and fricatives were both significant ($F(1, 45) = 14.53$, $p < .001$), due to the reversed CL bias for the fricatives. Taken together, the present results of an LC bias for plosives and nasals, and of CL bias for fricatives, supports the hypothesis that the LC bias is learned and operates at a phonetic category level, rather than the hypothesis stating that it is a bias at the global level.

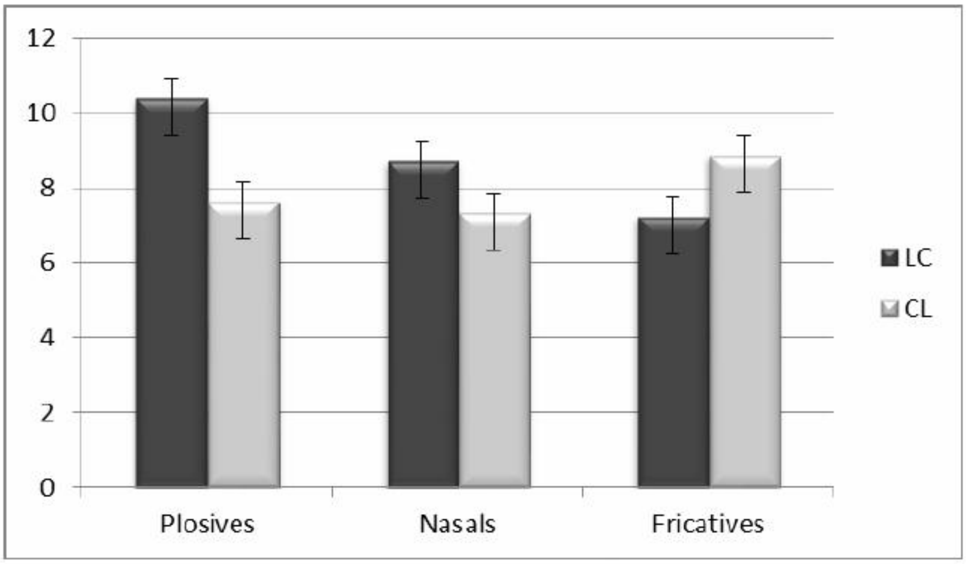

Figure 3 Mean orientation times (and SE) to the LC and CL stimuli. Left panel: plosive consonants (from Gonzalez-Gomez & Nazzi, 2012); Middle panel: nasal consonants (Experiment 1); Right panel: fricative consonants (Experiment 2).

4. General Discussion

The goal of the present study was to explore how, and the level at which, phonotactic acquisitions operate. The LC bias was used to explore this question, given that this bias is not uniformly present in the French lexicon. Indeed, our analyses revealed that the LC bias is found for plosive and nasal sequences, but not for fricative sequences (see Fig. 1 & 2). This asymmetry allowed us to explore whether this bias operates according to overall cumulative frequencies, that is, in a global way, or whether it operates according to different subcategories, in this case determined by manner of articulation. Two experiments were conducted exploring infants' preference for LC and CL sequences, one with nasals (Exp. 1) and one with fricatives (Exp. 2), and compared with the results obtained by Gonzalez-Gomez and Nazzi (2012) for plosives. The results of Experiments 1 & 2 showed an LC preference for nasals, extending the bias previously found for plosives, but the opposite CL pattern for fricatives.

The present results establish that infants' preference for LC sequences is not general, but appears to depend on the properties of the adult lexicon, which is likely to be reflected in the input (although this should be directly verified in future research). Thus infants preferred listening to LC sequences when involving plosives and nasals, but preferred CL sequences when presenting fricatives. This is in line with the French lexicon analyses showing an LC advantage for plosives and nasals but not for fricatives. Interestingly, the frequency analysis for fricatives was not as clear cut as the findings for plosives and nasals, in the sense that no input bias was found when analyzing sequences in all positions within the words (see Figure 1). If infants' bias was determined at that level, this could eventually explain the lack of an LC bias with fricatives, but it could not explain the finding of a CL bias. On the contrary, this bias can be explained by the frequency analysis restricted to word-initial sequences, for which there is a clear advantage for CL sequences (see Figure 2). This would be in line with the evidence suggesting that infants are more sensitive to onsets than other positions (Zamuner, 2006, Swingley, 2005). One condition for such a learning mechanism to work would be that infants are able to retrieve enough multisyllabic words from fluent speech. Although early findings failed to find evidence of such capacities before 12 months of age in French-learning infants (Nazzi, et al., 2006), more recent studies could establish such abilities by 8 months of age, both in Canadian-French (Polka & Sundara, 2012) and Parisian-French (Mersad & Nazzi, 2012; Nazzi et al., in preparation) infants.

Furthermore, the fact that 10-month-old infants were sensitive to the frequency differences of the LC phonotactic dependency for the three classes of consonants contrasted by manner of articulation (plosives, nasals, fricatives), indirectly shows that they are sensitive to this phonological feature, and that they can use it to make categories, and eventually use these categories to compute statistics and learn different phonological rules. These findings extend the evidence in the literature showing that very early in life infants are sensitive to different phonological features, such as manner (Eimas, & Miller, 1980; Hallé, & Boysson-Bardies, 1996; Jusczyk, Goodman, & Baumann, 1999) and place of articulation (Jusczyk, & Aslin, 1995; Swingley, & Aslin, 2000; 2002; Fenell and Werker, 2003).

Additionally, these results are in line with several studies showing that infants are sensitive to natural class features and that these features impact on how they find phonotactic regularities in artificial language experiments (Saffran and Thiessen, 2003; Cristia & Seidl, 2008; Cristià, Seidl, & Gerken, 2008; Seidl & Buckley, 2005). Given that phonological and phonotactic regularities are often governed by natural classes (Kuo, 2009), these results further show that phonological features can influence the acquisition of phonological and phonotactic regularities. Our study however is the first to show such effects for the acquisition of the native language phonotactic properties prior to the visit to the lab.

The present research is a first attempt at exploring the question about the level of generalization at which phonotactic acquisitions operate. Consequently, there are still lot of different questions and possibilities that have to be explored in future studies. For example, an analysis of Lexique 3 shows that out of 40 possible consonant pairs (5 labials: /p/, /b/, /f/, /v/, /m/; 8 coronals: /t/, /d/, /s/, / ʃ /, /z/, /ʒ/, /n/, /l/), five pairs (d-b, s-b, ʃ -f, s-v and ʒ-b) showed a reversed frequency bias, that is, more frequent coronal-labial than labial-coronal sequences, and these pairs include both plosives and fricatives. These results open the possibility for future research to further explore whether the LC bias really operates at a phonetic category level, or whether it operates at an "item-based" level, such that infants learn the relative frequency of the LC and CL sequences for each individual pair of consonants. Thus, for the specific pairs of phonemes identified above that have a bias opposite to their phonetic category (that is a plosive pair with a CL bias or a fricative pair with an LC bias), item-based and phonetic category learning would predict different preferences. Moreover, further research is needed, testing different other kinds of phonotactic patterns. For example, such research could be extended to vocalic phonotactic dependencies, given evidence that consonants and vowels play different roles at different linguistic processing levels, which suggest that consonants might be more important than vowels at the lexical level (Nespor, Peña, & Mehler, 2003; Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet & Butler, 2009). These and many other questions will need to be clarified in future research.

In conclusion, the present study is the first piece of evidence showing that the acquisition of a phonotactic property of the native language, here the LC bias, is made at the phonetic category level. The present findings thus suggest that phonological features can play a role in the acquisition of phonotactic regularities.

5. Acknowledgments

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Non-published additional experiments

As previously mentioned, a more detailed analysis of Lexique 3 revealed that out of 40 possible consonant pairs (5 labials: /p/, /b/, /f/, /v/, /m/; 8 coronals: /t/, /d/, /s/, /ʃ/, /z/, /ʒ/, /n/, /l/), five pairs (d-b, s-b, ʃ-f, s-v and ʒ-b) showed a reversed frequency bias, that is, more frequent coronal-labial than labial-coronal sequences, including both plosive and fricative sequences. Thus, two possible interpretations remain of how infants learn these phonotactic dependencies. The first one is that infants acquire these non-adjacent dependencies at the level of phonetic categories as it was argued in the previous paper. In this case category learning would predict an LC preference for all the pairs of plosives including the one showing a CL advantage, and a CL preference for all the pairs of fricatives, including those having a frequency advantage for LC in the lexicon. The second possibility is that infants learn those biases at the level of phonetic pairs. In this case item-based learning would predict for the five CL pairs a preference for CL sequences and an LC preference for all other pairs.

To explore these possibilities, two further experiments were conducted. The first experiment tested two pairs of plosives, one pair having an LC advantage and the other pair having a CL advantage. Similarly, the second experiment tested two pairs of fricatives, one with an LC bias and the other one with a CL bias.

Experiment 3 Plosives

Method

Participants. Two different groups of sixteen 10-month-old infants from French-speaking families were tested (mean age = 10 months 13 days; range: 10 months 1 day – 26 days; 14 girls, 18 boys). The data of five additional infants were not included in the analyses due to fussiness/crying.

Stimuli

Experiment 3a. (Pair with a LC bias). Twelve monosyllabic C1VC2 items were selected, combining the labial consonant “p” and the coronal consonant “t.” There were 6 items with a labial-coronal (LC) structure (pVt: /pɔ̃t/, /pat/, /put/, /pɔt/, /pɛ̃t/, /pot/) and 6 items with a coronal-labial (CL) structure (tVp: /tɔ̃p/, /tap/, /tup/, /tɔp/,

/tɛ̃p/, /top/). Items in both lists were made up of exactly the same consonants and vowels.

Experiment 3b. (Pair with a CL bias). Twelve monosyllabic C1VC2 items were selected, combining the labial consonant “b” and the coronal consonant “d”. There were 6 items with a labial-coronal (LC) structure (bVd: /bɔ̃d/, /bad/, /bud/, /bɔd/, /bɛ̃d/, /bod/) and 6 items with a coronal-labial (CL) structure (dVb: /dɔ̃b/, /dab/, /dub/, /dɔb/, /dɛ̃b/, /dob/). Items in both lists were made up of exactly the same consonants and vowels.

Vowels across all the experiments were chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the C1V, VC2 and C1VC2 sequences of phonemes according to the Lexique 3 database. The stimuli were recorded in a sound-attenuated booth by a French female native speaker who was naive to the hypotheses of the study. Two tokens of each item were selected. Two LC lists were created, one containing the first tokens of each LC items and the other the second tokens. Within each list, the 6 items were arranged in random order, and then repeated once in a different random order, leading to a list of 12 items. Two CL lists were constructed in the same way. The duration of all the lists was 18.00 s.

Procedure and Apparatus. Same as in Experiment 1

Results and Discussion

Mean orientation times to the LC and CL lists in Experiments 3a & 3b were calculated for each infant. Group averages are presented in Figure 4. The means for the group in Experiment 3a were (M_{LC} = 9.20 s, SD = 2.86 s; M_{CL} = 6.47 s, SD = 2.93). This pattern was present in 13 of the 16 infants tested (binomial test p = .011). The means for the group in Experiment 3b were (M_{LC} = 8.80 s, SD = 2.96 s; M_{CL} = 6.73 s, SD = 2.19). This pattern was present in 13 of the 16 infants tested (binomial test p = .011). A 2-way ANOVA with the between-subject factor of Experiment (3a versus 3b) and the within-subject factor of lexical structure (LC versus CL) was conducted. The effect of the lexical structure was significant (F(1,30) = 18.89, p < .001) showing that infants have longer orientation times for the LC lists. In addition neither the effect of experiment (F(1,30) = .75, p = .93) nor the interaction between experiment and lexical structure reached significance (F(1,30) = .35, p = .55).

Planned comparisons confirmed that the lexical structure effect was significant in both Experiment 3a F(1, 30) = 12.22, p = .001) and Experiment 3b (F(1, 30) = 7.02, p = .01). These results suggest that infants acquire the LC bias at the level of phonemic categories, rather than by phonemic pairs. However, Experiment 4 further explored this possibility, testing fricative consonants. This is crucial given that, as a phonetic category, fricatives show a CL advantage.

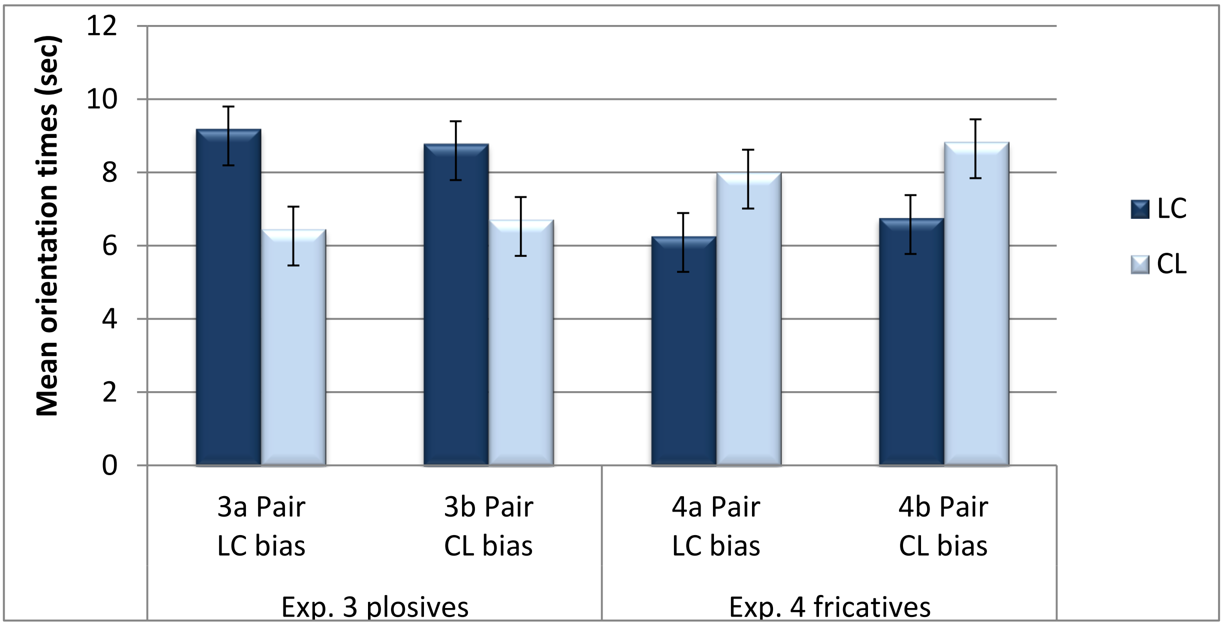

Figure 4. Mean orientation times (and SE) to the LC and CL stimuli. Left panel: plosives (Exp. 3): pair with an LC bias (3a: LC /p/-/t/ vs CL /t/-/p/), and pair with a CL bias (3b: LC /b/-/d/ vs CL /d/-/b/). Right panel: fricatives (Exp. 4): a pair with an LC bias (4a: /f/-/s/ vs /s/-/f/) and a CL pair (4b: /f/-/ʃ/ vs /ʃ/-/f/).

Experiment 4 Fricatives

Method

Participants. Two different groups of sixteen 10-month-old infants from French-speaking families were tested (mean age = 10 months 13 days; range: 10 months 1 day – 26 days; 13 girls, 19 boys). The data of six additional infants were not included in the analyses due to fussiness/crying.

Stimuli.

Experiment 4.a (Pair with a LC bias) Twelve monosyllabic C1VC2 items were selected, combining the labial consonant “f” and the coronal consonant “s” 6 items with a labial-coronal (LC) structure (fVs: /fɔs/, /fis/, /fɑ̃s/, /fus/, /fys/, /føs/) and 6 items with a coronal-labial (CL) structure (sVf: /sɔf/, /sif/, /sɑ̃f/, /suf/, /syf/, /søf/). Items in both lists were made up of exactly the same consonants and vowels.

Experiment 4.b (Pair with a CL bias) Twelve monosyllabic C1VC2 items were selected, combining the labial consonant "f" and the coronal consonant "ʃ" 6 items with a labial-coronal (LC) structure (fVʃ: /fɔʃ/, /fiʃ/, / fɑ̃ʃ/, /fuʃ/, /fyʃ/, /føʃ/) and 6 items with a coronal-labial (CL) structure (ʃVf: /ʃɔf/, /ʃif/, /ʃɑ̃f/, /ʃuf/, /ʃyf/, /ʃøf/). Items in both lists were made up of exactly the same consonants and vowels.

As in Experiment 3, all vowels across the experiments were chosen in order to obtain balanced adjacent dependencies between the LC and CL lists. All manipulation of the stimuli and the duration of all the lists was the same as in Exp. 3 (18.00 s.).

Procedure and Apparatus. Same as in Experiment 1

Results and Discussion

Mean orientation times to the LC and CL lists in Experiments 4a & 4b were calculated for each infant. Group averages are presented in Figure 4. The means for the group in Experiment 4a were (M_{LC} = 6.17 s, SD = 2.20 s; M_{CL} = 8.23 s, SD = 2.15 s). This pattern was present in 13 of the 16 infants tested (binomial test p = .011). The means for the group in Experiment 4b were (M_{LC} = 6.77s, SD = 2.84 s; M_{CL} = 8.84 s, SD = 3.75 s). This pattern was present in 14 of the 16 infants tested (binomial test p = .002). A 2-way ANOVA with the between-subject factor of Experiment (4a versus 4b) and the within-subject factor of lexical structure (LC versus CL) was conducted. The effect of the lexical structure was significant (F(1,30)= 15.09, p<.001) showing that infants tend to have longer orientation times for the CL lists. Additionally, the effect of experiment was not significant (F(1,30)= .52, p=.47) nor the interaction between experiment and lexical structure (F(1,30)= .0001, p=.99). Planned comparisons confirmed that the lexical structure effect was significant in both Experiment 4a F(1, 30) = 7.50, p = .01) and Experiment 4b (F(1, 30) = 7.58, p = .009). These results confirm the results of Experiments 3a & 3b showing that infants do not react to the frequency differences of the phonemic pairs presented, but they react to the frequency observed at the level of phonetic categories determined by manner of articulation.

At which level are non-adjacent phonological acquisitions acquired?

The results of the four experiments presented in this section revealed that:

- The LC preference found is not general, but appears to depend on the properties of the adult lexicon/input.
- These modulations appear to happen at the level of classes of phonemes that share the same manner of articulation.
- Infants appear to be sensitive to natural class features in the acquisition of their native language
- These findings are congruent with previous findings showing that phonetic features constrain the acquisition in the laboratory of the phonotactic regularities of simple artificial languages (Saffran and Thiessen, 2003; Cristia & Seidl, 2008; Seidl & Buckley, 2005).

➔ Based on this evidence, it seems that this perceptual bias is acquired at the level of classes of consonants defined by their manner of articulation.

1.3 Analyzing the role of maturation:

The case of preterm Infants

"Language shapes the way we think,
and determines what we can think about."
Benjamin Lee Whorf

As previously mentioned, there is a controversy about the origins of the LC bias. Two different but not exclusive interpretations have been offered. The first possibility is that this bias is trigger by articulatory/motor constraints as MacNeilage and colleagues have argued (1999, 2000). The second possibility postulates a perceptual origin (based on the linguistic input) as Nazzi and collaborators proposed (2009, 2012).

In this section we explore these two possibilities by testing a population of infants that has different maturational characteristics than the typically-developing term infants tested so far. These differences in maturation will allow us to explore whether the emergence of the LC bias is due to input exposure or whether the preference for LC sequences is due to maturational factors, such as a pre-wired preference emerging between 7 and 10 months of post-term maturation.

To do so, we tested the emergence of the LC bias in a group of preterm infants born ± 3 months before term, and compared their performance to a group of full-term infants matched in maturational age, and a group of full-term infants matched in chronological age. The importance of this experiment lies in the possibility of distinguishing maturational level and time of exposure to the linguistic input.

The results of this experiment will bring at the same time information about the origin of the LC bias, the role of maturation and input exposure on early speech perception, and the development of language in preterm infants.

Nayeli Gonzalez-Gomez & Thierry Nazzi (In revision in *Developmental Science*)

Phonotactic acquisition in healthy preterm infants

Abstract

Previous work showed that preterm infants are at higher risk for cognitive/language delays than full-term infants. Recent studies, focusing on prosody (i.e., rhythm, intonation), suggested that prosodic perception development in preterms is indexed by maturational rather than chronological/listening age. However, because prosody is heard in-utero, and preterms thus loose significant amounts of prenatal prosodic experience, both their maturation level and their prosodic experience (listening age) are shorter than that of full-terms for the same chronological age. This confound does not apply to the acquisition of phonetics/phonotactics (i.e., identity and order of consonants/vowels), given that consonant differences in particular are only perceived after birth, which could lead to a different developmental pattern. Accordingly, we explore the possibility that consonant-based phonotactic perception develops according to listening age.

Healthy French-learning full-term and preterm infants were tested on the perception of consonant sequences in a behavioral paradigm. The pattern of development for full-term infants revealed that 7-month-olds look equally at labial-coronal (i.e., /pat/) compared to coronal-labial sequences (i.e., /tap/), but that 10-month-olds prefer the labial-coronal sequences that are more frequent in the French lexicon. Preterm 10-month-olds (having 10 months of phonetic listening experience but 7 months of maturational age) behaved as full-term 10-month-olds. These results establish that preterm developmental timing for consonant-based phonotactic acquisition is based on listening age (experience with input). This questions the interpretation of previous results on prosodic acquisition in terms of maturational constraints, and raises the possibility that different constraints apply to the acquisition of different phonological subcomponents.

Key words: preterm infants, speech perception, phonological acquisition, maturation, listening experience

Introduction

According to estimations of the World Health Organization, each year 9.6% of all births are preterm in the world, which translates in more than 12 million preterm births per year. Moreover, the incidence of preterm birth has been increasing dramatically over the past 20 years in some developed countries, such as the United Kingdom and the United States (Beck et al., 2010; Callaghan, MacDorman, Rasmussen, & Lackritz, 2006; National Center for Health Statistics USA). Given the number of preterm births, many studies have focused on the impact and the consequences that preterm birth has on development. These studies converge in showing that even healthy preterm infants, who show no obvious neurological problems, have a higher risk of developing speech, language, attention or motor impairments during the school years (Hack et al., 1994; Briscoe & Gathercole, 1998; Luoma, Herrgård, Martikainen, & Ahonen, 1998; Grunau, Whitfield, & Davis, 2002; Crunelle, Le Normand, & Delfosse, 2003; Pritchard et al., 2009; Guarini et al., 2010; Sansavini et al., 2010). One explanation for the later neurodevelopmental difficulties in healthy preterm infants, who show no obvious neurological problems, might come from the presence of cerebral white matter microstructural alterations in the absence of brain damage (Anjari et al., 2007; Soria-Pastor et al., 2008; Gimenez et al., 2008).

In the language domain, preterm birth has been found to increase the risk of deficits in the preschool and school years at different stages of processing levels (for a recent review, see Sansavini et al., 2010). At the perceptual level, preterm children show poorer auditory discrimination and memory, reading difficulties, and lower receptive understanding than their matched controls. At the production level, preterm children also present different deficits such as poor vocabulary, a specific delay in verbal processing and reasoning, and less complex expressive language (on both issues, see Jansson-Verkasalo et al., 2004; Grunau, Kearney, & Whitfield, 1990; Crunelle et al., 2003; Luoma, Herrgård, Martikainen, & Ahonen, 1998; Guarini et al., 2009, for preschool children; and Crunelle et al., 2003; Guarini et al., 2010 for school age children). However, it remains unclear whether these deficits are due to a general cognitive delay triggered by immaturity as has been previously suggested (Ortiz-Mantilla, Choudhury, Leevers, & Benasich, 2008; Rose, Feldman, & Jankowski, 2009), or if these deficits are due to impairments in specific language abilities (Guarini et al., 2009, 2010). Uneven proficiency in different language subdomains are expected only in the latter case.

While many preterm studies have focused on the impact of preterm birth on language acquisition during the past decades, most of these studies have concentrated on the effects of prematurity during the preschool or school years. The effect of preterm birth on the early development of language, much of which occurs during the first year of life (making this period crucial for language acquisition, c.f. Kuhl, 2000), remains little explored. Additionally, most of the studies on the early development have focused on the effects that premature birth has on the production of preverbal utterances and gestures. These studies found that preterm infants in their first year look at their mothers less (Malatesta et al., 1986; Barrat, Roach, & Leavitt, 1992), show more gaze aversion (Crnic et al., 1983), less facial expressions (Malatesta et al., 1986; Crinic et al., 1983; Van Beck Hopkins, & Hoeksma, 1994; Schmücker et al., 2005) and less vocalization (Beckwith, Sigman, Cohen, & Parmelee, 1977; Barrat et al., 1992) than full-term infants of the same chronological age. This shows that premature birth also has a negative impact on the early development of preverbal utterances and gestures.

There are even fewer studies exploring preterm infants' early speech perceptual abilities. Additionally, most of these studies looked at the acquisition of prosody (that is, the music of language such as its rhythm, its intonation). Peña and colleagues (2010) and Bosch (2011) have both explored linguistic rhythm discrimination, while Herold and collaborators (2008) studied stress pattern discrimination. All these studies conclude that performance of preterm infants is likely to be indexed by their corrected/maturational age (corresponding to their chronological age minus the duration of their prematurity) rather than by their chronological age (calculated from the infant's birth). Indeed, preterm infants were found to have acquired distinctions specific to their native language that allow them to distinguish their native language from another rhythmically similar language at about 9 months of age (6 months corrected age), while full-term infants are able to make this distinction already by the age of 6 months (Peña et al., 2010; Bosch, 2011). Moreover, 4- and 6-month-old German preterm infants were not able to distinguish between a trochaic stress pattern (stress on the first syllable), which is characteristic of German words, and an iambic stress pattern (stress on the second syllable), whereas full-term infants do so at both 4 and 6 months (Herold et al., 2008; Höhle, Bijeljac-Babic, Herold, Weissenborn & Nazzi, 2009). Two other studies did not explore prosodic perception, but focused on vowel discrimination (Figueras Montiu & Bosch, 2010) and word segmentation (Bosch, 2011). Both studies revealed that preterm infants were not performing at the level of term infants of the same chronological age, which might suggest delays in the development of these abilities in preterm infants. However, the authors note that the tasks and stimuli used in these studies might have put too much cognitive load on the preterm infants' processing abilities, leaving the possibility of better performance in simpler tasks.

The above results suggest that the development of prosodic processing in preterm infants is affected during the first year of life. Many factors could explain this delay in early prosodic development. One possibility is that preterm infants need more time to learn prosodic features due to maturational differences (Herold et al., 2008; Peña et al., 2010). A second possibility is that prosodic sensitivity impaired (Herold et al., 2008). A third possibility could be due to differences in the quality and the amount of input that preterm infants perceived while being in incubator care (Herold et al., 2008). A fourth possibility is to ascribe the delay to cerebral white matter microstructural problems, which have been shown to be present in preterm infants even in the absence of brain damage (Anjari et al., 2007; Soria-Pastor et al., 2008; Gimenez et al., 2008). A fifth possibility is related to cascading effects that can take place when the typical developmental timing of the brain is altered when some subcomponents do not develop in the typical period or at the typical speed as suggested by Karmiloff-Smith, (1997, 2009) and Guarini and colleagues (2009, 2010). All these possibilities can explain the delay find for prosody, for which development was predicted by maturation age, and would predict a similar outcomes for prosody and phonetic/phonotactics.

However, we propose that these prosodic developmental delays might proceed from yet another factor, namely a loss of prenatal experience, which would directly affect prosodic acquisition but not phonetic/phonotactic acquisition. Indeed, the basal morphological structures of the auditory system are already developed at 23 weeks of gestational age (GA; Arabin, van Straaten & van Eyck, 1988), and while some fetuses present their first behavioral responses to auditory stimuli from 24 weeks onward, all fetuses respond at 28 weeks GA (Lecanuet, Granier-Deferre, Jacquet, & Busnel, 1992; Morlet, Desreux, & Lapillone, 1999; Birnholz & Benacerral, 1983). Given these auditory abilities, several studies have explored and showed that prosodic information is already heard and processed in utero. Indeed, during the last trimester of pregnancy, fetuses were able to discriminate low from high musical notes (Lecanuet, Graniere-Deferre, Jacquet, & DeCasper, 1999), or a female from a male voice (Lecanuet et al., 1992). Therefore, it is unclear whether the delays found in preterm infants in the studies on prosodic processing/acquisition are due to maturation differences as previously suggested, or to differences in the duration of exposure to prosodic features between full-term and preterm infants (given the loss of prosodic prenatal experience in preterm infants).

Such an interpretation problem would not apply to the acquisition of phonetics/phonotactics. Indeed, several studies have shown that low frequencies, which mostly carry prosodic information, are well preserved in utero, while there is greater attenuation of the higher frequencies relevant to phoneme identification (Armitage, Baldwin, & Vince, 1980; Garnier-Deferre, Lecanuet, Cohen, & Busnel, 1985; Griffith et al., 1994). Second, two studies have tested adult identification of speech sounds recorded within the uterus of a pregnant woman (Querleu et al., 1988) or a pregnant sheep (Griffith et al., 1994). The results showed that only about 30% of the phonemes were recognized. Adults made more errors on consonants than vowels (the former depending more on higher frequencies), in particular for place and manner information (Griffith et al., 1994). Therefore, these studies establish limited identification of phonemes based on information available in utero by adults, which moreover does not necessary reflect the perceptibility of speech by the fetus. Regarding fetal perception, several studies have shown that near-term fetuses are able to discriminate the vowels /a/ from /i/ embedded in different contexts (/a/ vs. /i/; /ba/ vs. /bi/; /babi/ vs. /biba/) by 35 weeks GA onwards but not at 27 weeks GA (Groome, Mooney, Holland, Bentz & Atterbury, 1997a; Groome et al., 1997b; Lecanuet et al., 1987; 1989; Shahidullah & Hepper, 1994). While these results might reflect some ability to discriminate vowel phonetic information, some of these authors have remarked that differences in the structure of formants of the vowels /a/ (F1 = 680Hz, F2 = 1200 Hz) and /i/ (F1 = 240Hz, F2 = 2160Hz) made that the syllable /ba/ sound louder than /bi/ (Lecanuet et al., 1999; Busnel, Granier-Deferre , & Lecanuet, 1992), opening the possibility that fetuses were reacting on the basis of prosodic properties of the stimuli. Lastly, to the best of our knowledge, there are no studies showing that fetuses are able to distinguish consonantal information.

Therefore, in order to evaluate the possibility that the delay for prosodic acquisition might be related to a loss in prenatal exposure, we tested preterm infants in a language subdomain that is not well perceived in utero, such as phonetics/phonotactics, and more particularly on consonantal features. As mentioned above, all previous explanations of the prosodic delay in preterms (maturational differences, white matter microstructural problems, cascading effects due to asynchrony in development…) would also predict a time-lag for phonetics/phonotactics, preterm infants performing less well than term infants of the same chronological age. On the contrary, if the delay is due to loss of prenatal exposure, then preterm and full-term infants of the same chronological age might fare similarly.

To compare the trajectory for phonetic/phonotactic development in preterm and full-term infants, the acquisition of the labial-coronal (LC) bias at the perceptual level was explored. The LC bias is defined as an advantage for LC words, that is words starting with a labial consonant (consonants articulated with one or both lips, i.e. sounds like /b/, /p/, /f/…) followed by a coronal consonant (consonants articulated with the flexible front part of the tongue in the front of the mouth cavity, alveolar, i.e. sounds like /t/, /d/, /n/…), as in the word “beta” over coronal-labial (CL) words (that is, words starting with a coronal consonant followed by a labial consonant, i.e., “tuba”). It is thus based on processing consonantal place information, which appears to be one of the poorest information transmitted in utero (Griffith et al., 1994). This bias has initially been found in typological studies showing that LC words are more frequent than CL words in many languages, including French, the language of the infants tested (c.f., Table 1, and MacNeilage & Davis, 2000; Vallée, Rousset, & Boë, 2001), and in early word production studies in which researchers found that during the 50-word-stage infants tend to produce significantly more LC than CL sequences (MacNeilage & Davis, 2000). The authors attribute the existence of this bias in different languages to articulatory constrains, arguing that LC sequences require less articulatory movements, thus they are easier to produce, than the opposite pattern, that is, the CL sequences (c.f. MacNeilage & Davis, 1999). More recently, the LC bias has been found in perception (Nazzi, Bertoncini & Bijeljac-Babic, 2009;

Gonzalez-Gomez & Nazzi, 2012), where infants start preferring to listen to LC words over CL words between 6 and 10 months of age. Interestingly, this perceptual preference was found even though 10-month-olds were not yet producing LC and CL sequences, suggesting that the bias might result from perceptual learning rather than production constraints as previously proposed in the literature. Furthermore this effect reflects sensitivity to non-adjacent dependencies, given that the LC bias involves a relation between two consonants that are separated by a vowel (c.f. Gonzalez-Gomez & Nazzi, 2012, for further discussion).

Table 1: Cumulative frequency of LC and CL French words (all words versus CVC words only) according to the adult database *Lexique 3* (New, et al., 2001).

	All words	CVC words only
Lab-Cor	71,822	6,808
Cor-Lab	42,772	1,179

Accordingly, the present study explores the emergence of a perceptual LC bias in preterm infants. As in previous studies, preterm infants, tested at 10 months of chronological age, were compared to two matched groups of full-terms: infants with the same chronological age (10 months) and infants with the same maturational age (7 months). We predicted that, on this phonotactic acquisition, preterm infants might be at the level of full-term 10-month-olds, due to the lack of prenatal exposure (and provided other factors such as developmental asynchrony or incubator noise do not affect this acquisition to a large extent). Alternatively, all other hypotheses would predict that preterms would perform below full-term 10-month-olds.

Materials and Methods

Participants

The data of 20 healthy preterm 10-month-old French-learning infants were included in the analyses (chronological age M = 10;10; range: 10;01-10;22; 10 girls, 10 boys, see Table 2 for their clinic characteristics). Preterm infants were recruited if, at birth, they had met four primary criteria: a) a gestational age ≤33 weeks, b) no indication of visual or hearing impairment, and c) normal neuropediatric examination, suggesting a lack of major cerebral damage (i.e. periventricular leukomalacia, intraventricular hemorrhage, hydrocephalus, retinopathy of prematurity) and congenital malformations, infants' brain status at birth being established by an MRI and/or by cranial ultrasound, and d) born in monolingual French-speaking families. All the preterm participants had an appropriated birth weight for their GA (no SGA were included).

Table 2: Clinical characteristics of the preterm participants

	GA (weeks)	Birth Weight (gr)	Apgar 1	Apgar 5	days of hospitalization	days on incubator care
Mean	29.7	1412	8.1	9.0	50.2	15.8
SD	2.18	427	1.0	0.7	19.6	5.8

Forty healthy full-term French-learning infants were recruited and their data included in the analyses to serve as control groups. These groups were constituted by matching each preterm infant with a full-term infant of the same maturational age (+/- 7 days) and a full-term infant of the same chronological age (+/- 7 days): 20 full-term 7-month-olds (M = 7;21; range: 6;28-8;25; 10 girls, 10 boys) and 20 full-term 10-month-olds (M = 10;08; range: 10;01-10;25; 8 girls, 12 boys). Four 7-month-olds and 14 10-month-olds came from the sample tested in the same experiment by Gonzalez Gomez and Nazzi (2012), while the other control infants were tested for the present study with the purpose of matching the infants to the preterm sample. The data of 3 full-term 7-month-olds and 2 full-term10-month-olds were excluded due to fussiness. All full-term infants had experienced normal birth (gestational age > 37weeks and birth weight > 2800g), and had no history of major cerebral damage and/or congenital malformations or visual or hearing impairments.

Note that the range of gestational ages of the preterm infants in the present study (26-33 weeks GA) is larger than the ranges of the infants used in the prosody studies (Peña, et al., 2010: 27-30 weeks GA; Herold, et al., 2008: 26-30 weeks GA). As a result, two sets of analyses were conducted, one with all infants, and one taking the subgroup of preterm infants within the 26-30 weeks GA range (n = 13), and their matched controls.

Stimulus

Twenty-four monosyllabic $C_1V_1C_2$ items were selected (see Table 3), twelve items with a labial-coronal (LC) structure and twelve items with a coronal-labial (CL) structure. Items in both lists were made up of exactly the same consonants, and the vowels were almost completely balanced across lists. Vowels had been chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the C_1V_1, V_1C_2 and $C_1V_1C_2$ sequences of phonemes according to the Lexique 3 database (New, et al., 2001), to ensure that infants react to the difference in the relative non-adjacent frequencies between LC and CL sequences and not to differences in adjacent properties. Due to this constraint on adjacent frequencies, we had to use a mix of both low frequency French words (n = 7) and pseudowords legal in French (n = 5, marked by * in Table 3) for both the LC and the CL lists.

The stimuli were recorded in a sound-attenuated booth by a French female native speaker. Two tokens of each item were selected. The duration of the LC and CL tokens was similar (559 vs. 550 ms, $t_{(44)} < 1$). Four lists were created: two lists with the twelve LC items (different tokens, the order of the items in the two lists being reversed) and two lists with the twelve CL items (same manipulation). The duration of all the lists was 18.0 s. Additionally, as in Gonzalez-Gomez and Nazzi (2012), parents filled out a questionnaire (adapted from Stoel-Gammon, 1989), in order to determine the babbling level of each infant, to latter compare the babbling production of preterm and full-term infants. This classification distinguishes three babbling levels:

- Level 1 (Precanonical vocalizations): Utterances composed of a vowel, a syllabic consonant, a consonant-vowel or vowel-consonant sequence in which the consonant is a glide or glottal, or any combination of the above (i.e. /a/, /m/, /wawə/).

- Level 2 (Canonical babbling): Utterances containing at least one consonant-vowel or vowel-consonant sequence in which the consonant is a true consonant, ot a glottal or glide one. The utterance could have more than one consonant or vowel, but the consonants would have to share the same place and manner of articulation (i.e. /ga/, /dIdə/, /aba/, /baba/, /mɛmɛ/).

- Level 3 (Variegated babbling): Utterances containing at least two true consonants differing in place or manner of articulation (i.e. /gabɛ/, /ədæp/, /batɛ/). This is the only level at which infants are able to produce LC or CL sequences.

Table 3: List of Labial-Coronal and Coronal-Labial CVC sequences used in the Experiment, the asterisk point to the pseudowords legal in French lexicon.

Labial-Coronal			Coronal-Labial		
Structure	**Word/ Pseudo-word**	**IPA**	**Structure**	**Word/ Pseudo-word**	**IPA**
$b^{v}d$	bonde	[bɔ̃:d]	**$d^{v}b$**	danbe*	[dɑ̃:b]
	bude*	[byd]		daube	[do:b]
	bad*	[bad]		dab*	[dab]
$p^{v}t$	pote	[pɔt]	**$t^{v}p$**	tempe	[tɑ̃:p]
	pinte	[pɛ̃:t]		tape	[tap]
	paute*	[po:t]		taupe	[to:p]
$b^{v}t$	botte	[bɔt]	**$t^{v}b$**	tube	[tyb]
	butte	[byt]		tombe	[tɔ̃:b]
	bath	[bat]		tab*	[tab]
$p^{v}d$	pad	[pad]	**$d^{v}p$**	dape*	[dap]
	paude*	[po:d]		dinpe*	[dɛ̃:p]
	pande*	[pɑ̃d]		dope	[dɔp]

Procedure and Apparatus

The experiment was conducted inside a sound-proof room, in a booth made of pegboard panels (bottom part) and a white curtain (top part). The test booth had a red light and a loudspeaker (SONY xs-F1722) mounted at eye level on each of the side panels and a green light mounted on the center panel. Below the center light was a video camera used to monitor infants' behavior.

A PC computer terminal (Dell Optiplex), a TV screen connected to the camera, and a response box were located outside the sound-proof room. The response box, connected to the computer, was equipped with a series of buttons. The observer, who looked at the video of the infant on the TV screen to monitor infant's looking behavior, pressed the buttons of the response box according to the direction the infant's head, thus starting and stopping the flashing of the lights and the presentation of the sounds, and recording the looking times. The observer and the infant's caregiver wore earplugs and listened to masking music over tight-fitting closed headphones, which prevented them from hearing the stimuli presented. Information about the duration of the head-turn was stored on the computer.

The classic version of the Head-turn Preference Procedure (HPP) was used (Jusczyk, Cutler, & Redanz, 1993). Each infant was held on a caregiver's lap in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented to it. Then, the red light on one of the side panels began to flash. When the infant turned in that direction, the stimulus for that trial began to play. The stimuli were delivered by the loudspeakers via an audio amplifier (Marantz PM4000). Each stimulus was played to completion or stopped immediately after the infant failed to maintain the head-turn for 2 consecutive seconds. If the infant turned away from the target by 30° in any direction for less than 2s and then turned back again, the trial continued but the time spent looking away (when the experimenter released the buttons of the response box) was automatically subtracted from the orientation time by the program. Thus, the maximum orientation time for a given trial was the duration of the entire speech sample. If a trial lasted less than 1.5 s, the trial was repeated and the original orientation time was discarded.

Each session began with two musical trials, one on each side to give infants an opportunity to practice one head-turn to each side. The test phase consisted of 8 trials divided in two blocs (in each of which the two lists of each structure were presented). The order of the different lists within each block was randomized.

Results

Regarding the perceptual data, mean orientation times to the LC and CL lists were calculated for each infant (c.f. Figure 1). After confirming that the distribution of the data in the three groups was normal, a 3-way ANOVA with the between-subject factor of group (preterm 10-month-olds, full-term 7-month-olds and full-term 10-month-olds) and the within-subject factor of lexical structure (LC versus CL words) was conducted. The effect of lexical structure was significant, $F(1, 57) = 15.24$, $p < .001$, such that overall infants had longer orientation times to LC than to CL lists. The effect of group was not significant, $F(2, 57) = 1.59$, $p = .21$. However, the interaction between group and lexical structure was significant, $F(2, 57) = 7.07$, $p = .002$, indicating that the effect of lexical structure changed between groups. Planned comparisons were conducted. They showed that the lexical structure effect was significant for the preterm group, $F(1, 57) = 14.28$, $p < .001$, who had longer orientation times to the LC sequences ($M_{LC} = 11.16$ s, SD = 2.50) than to the CL sequences ($M_{CL} = 8.58$ s, SD = 3.27). The lexical structure effect was also significant for the full-term 10-month-olds, $F(1, 57) = 14.44$, $p < .001$, who had longer orientation times for the LC sequences (M_{LC} = 9.85 s, SD = 2.93 s; M_{CL} = 7.26 s, SD = 2.40 s). On the contrary, it was not significant for the full-term 7-month-olds, F(1, 57) = 0.66, p = .41, who did not show any preference for the LC sequences (M_{LC} = 8.92 s, SD = 2.61 s; M_{CL} = 9.47 s, SD = 2.89). The comparisons further showed that the interaction between lexical structure and group restricted to the preterm 10-month-olds and the full-term 7 month-olds was significant, F(1, 57) = 10.56, p = .001, while that same interaction restricted to the preterm 10-month-olds and the full-term 10-month-olds was not significant, F(1, 57) < 1, p = .98. These results establish that both preterms and full-terms have acquired the LC bias by 10 months. Hence, by 10 months of age, both preterm and full-term infants are sensitive to non-adjacent phonological dependencies of their native language. Importantly, the performance of the preterm 10-month-olds was indistinguishable from the performance of the full-term infants of the same chronological age (10 months) and different from the performance of the full-term infants of the same maturational age (7 months).

Given that the range of gestational ages of the preterm infants in the present study is larger (26-33 weeks GA) than the ranges of the infants used in the prosody studies (Peña, et al., 2010: 27-30 weeks GA; Herold, et al., 2008: 26-30 weeks GA), the difference in the pattern of results between prosody and phonotactics might be due to these differences in gestational ages. To explore this possibility, a second analysis restricted to the preterm infants within the same gestational age range as the above two studies (26-30 weeks GA, n = 13) and their matched controls at 7 and 10 months of age was conducted. After confirming that the distribution of the data in the three groups was normal, a 3-way ANOVA with the between-subject factor of group (preterm 10-month-olds born between 26-30 weeks GA, full-term 7-month-olds and full-term 10-month-olds) and the within-subject factor of lexical structure (LC versus CL words) was conducted. The effect of lexical structure was significant, F(1, 36) = 10.58, p=.002, such that overall infants had longer orientation times to LC than to CL lists. The effect of group was not significant, F(2, 36) = 2.37, p = .10. However, the interaction between group and lexical structure was significant, F(2, 36) = 4.18, p = .02, indicating that the effect of lexical structure changed between groups.

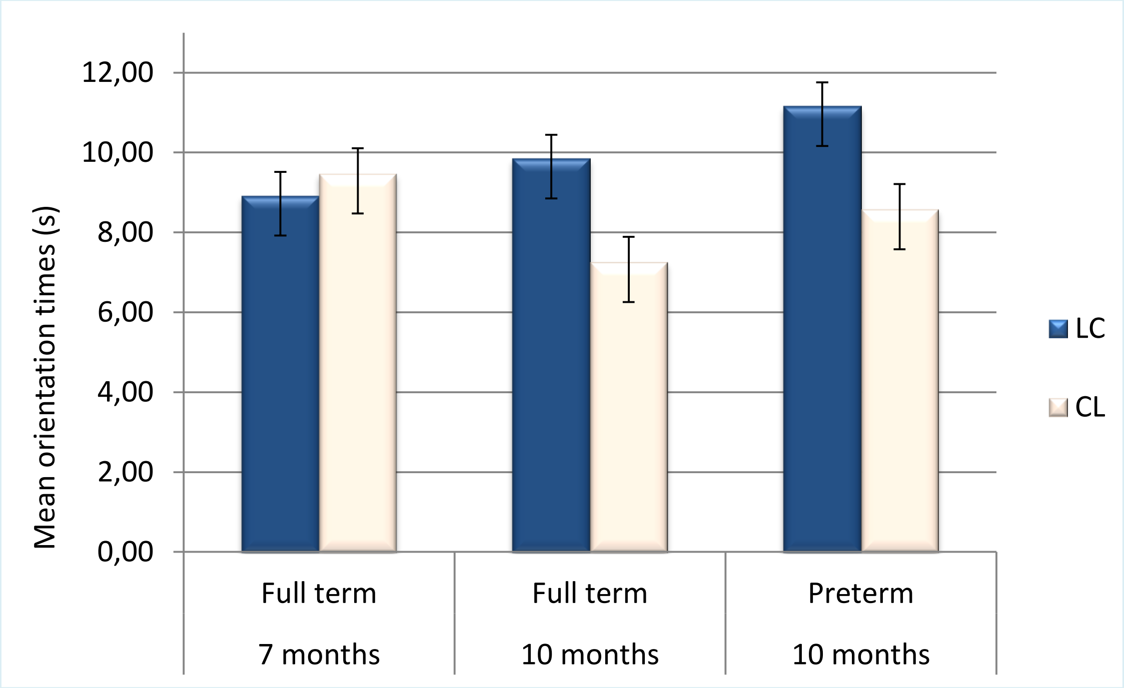

Figure 1. Mean orientation times (and standard error of the mean) to the LC versus CL stimuli for the full-term 7-month-olds, the full-term 10-month-olds, and the preterm 10-month-olds.

Again, planned comparisons were conducted. They showed that the lexical structure effect was significant for the preterm group, F(1, 36) = 11.17, p = .002, who had longer mean orientation times to the LC sequences (M_{LC} = 11.79 s, SD = 2.35) than to the CL sequences (M_{CL} = 8.60 s, SD = 3.67). The lexical structure effect was also significant for the full-term 10-month-olds, F(1, 36) = 7.58, p = .009, who had longer orientation times for the LC sequences (M_{LC} = 9.72 s, SD = 2.58 s; M_{CL} = 7.10 s, SD = 2.01 s). On the contrary, it was not significant for the full-term 7-month-olds, F(1, 36) = .21, p = .65, who did not show any preference for the LC sequences (M_{LC} = 9.58 s, SD = 2.45 s; M_{CL} = 10.01 s, SD = 3.30). The comparisons further showed that the interaction between lexical structure and group restricted to the preterm 10-month-olds born between 26-30 weeks GA and their matched full-term 7 month-olds was significant, F(1, 36) = 7.22, p = .01, while that same interaction restricted to the preterm 10-month-olds and their matched full-term 10-month-olds was not significant, F(1, 36) = .17, p = .67. These results confirm the pattern found in our larger preterm group, thus ruling out gestational differences as a possible explanation for the different outcomes of our results compared to those on prosody (Peña, et al., 2010; Herold, et al., 2008).

Regarding production (see Figure 2), the results of the babbling questionnaire for the preterm 10-month-olds show that 8 infants produced vowel and semi-vowel sounds (babbling level 1), and 12 infants produced sequences that are composed of consonant-vowel alternations, in which the repeated consonant was a true consonant (babbling level 2). This contrasts with the results of the full-term infants who, except for 2 7-month-olds still at babbling level 1, were all at babbling level 2. Note that none of the infants in the present study produced sequences with varied consonants (babbling level 3), thus none produced LC and CL structures. Chi2 tests showed that babbling distributions were significantly different between the preterm and the full-term 10-month-olds, chi2 (ddl = 1) = 10.00, p = .003, and marginally significant between the preterm 10-month-olds and the full-term 7-month-olds, chi2 (ddl = 1) = 4.80, p = .05. This establishes that preterm production performance is at the level of, or lower, than that of full-term 7-month-olds. Lastly, we tested whether the preterm infants at babbling level 1 and those at babbling level 2 differed in their performance on the phonetic/phonotactic task, but found no difference, $t_{(19)} = .51$, $p = .63$.

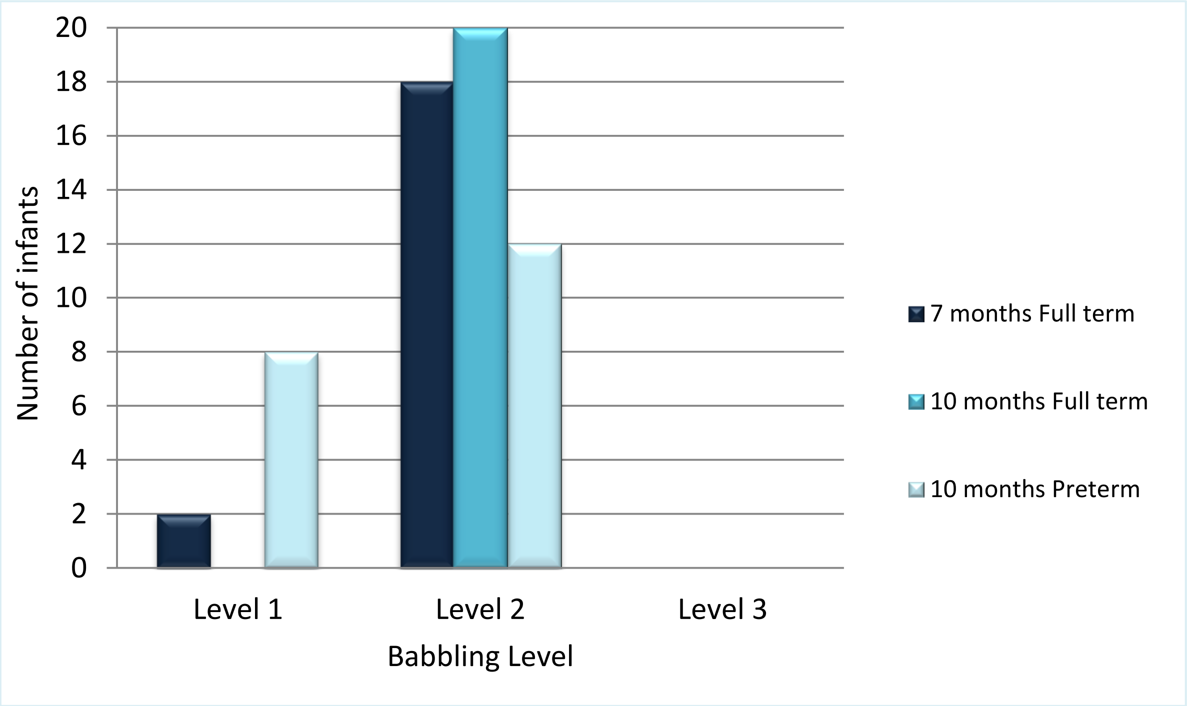

Figure 2. Number of infants at each babbling level for the preterm 10-month-olds, the full-term 10-month-olds and the full-term 7-month-olds.

Discussion

The present study establishes that preterm as well as full-term infants at 10 months, but not full-term infants at 7 months, prefer LC structures over CL ones. With respect to the development of full-term infants, the present results confirm the emergence of a perceptual labial-coronal (LC) bias between the ages of 7 and 10 months. Furthermore, they support the interpretation that by 10 months, infants have learned some phonological dependencies present in the French lexicon, specifically, the general predominance of LC sequences over CL sequences in French words (as previously argued by Nazzi, Bertoncini, & Bijeljac-Babic, 2009 and Gonzalez-Gomez & Nazzi, 2012). Indeed, while it was unclear from the previous studies whether the LC bias was triggered by maturation or by exposure to linguistic input, the latter interpretation is reinforced by the present results, showing that the development of phonotactics in preterm infants is predicted by their listening age (the time of exposure to the linguistic input), not their maturational age. Given this evidence, we predict that infants learning a language that does not show a labial-coronal advantage in the input would not present an LC perceptual bias by 10 months. Japanese-learning infants could be tested since Japanese constitutes such a language (c.f. MacNeilage, Davis, Kinney, & Matyear, 1999; Tsuji, Gonzalez-Gomez, Medina, Nazzi, & Mazuka, in revision).

With respect to the development of preterm infants, the fact that the preterm 10-month-old perceptual pattern resembles that of the full-term 10-month-olds (same duration of listening experience) and that this pattern is different from the pattern of the full-term infants at 7 months of age (same maturational age) suggests that the developmental timing for the acquisition of the LC bias is based on duration of input experience. This raises the possibility that this acquisition relies on the same mechanisms that are relied upon by full-term infants. Moreover, this lack of delay is compatible with the possibility that these neural networks are already mature (and not too severely affected by white matter structural problems) by the time of the birth of the preterms, which might further explain why this acquisition is not affected in spite of the developmental asynchrony between infants' general brain maturation and the moment they start having access to phonetic information. Lastly, the lack of performance difference in this perceptual task between the preterm and full-term infants suggests that this acquisition was not significantly affected by the period in which infants were hospitalized (M = 50 days) and placed in incubator (M = 15 days), during which it is likely that they received reduced or degraded speech stimulation. This in turn would suggest that it is the duration over which infants are exposed to speech (here 10 months) rather than a specific amount of experience, that is a key factor in these acquisitions.

In summary, we found no delay in the emergence of the phonotactic LC perceptual bias in preterm compared to full-term infants. This pattern of results is different from the developmental timing differences found for prosody (Peña, et al., 2010; Bosch, 2011; Herold, et al., 2008), vowel discrimination (Figueras & Bosch, 2010) and segmentation (Bosch, 2011). In the following, we discuss a few possibilities that might explain these differences, although further studies with preterms will be required to fully understand these differences. With respect to vowel discrimination, one possibility is that consonant and vowel acquisition do not start at the same time, because vowels are more salient than consonants, and that some vocalic acquisition might start in utero. However, as noted by Figueras and Bosch (2010) themselves, another possibility is that they tested infants with stimuli from several talkers, which might have made the task cognitively too demanding, and is also one reason advanced for the delay found for the preterm infants in segmentation studies (Bosch, 2011). This could be tested for example by replicating the present experiment using stimuli recorded by several speakers, and determine if it affects preterm infants more severely than full-term infants.

The present results also have implications for the interpretation of the results obtained for prosodic acquisition. Given that phonotactic development seems to be based on input experience, the delay found in prosody could be explained by different hypotheses. A first possibility, compatible with the interpretations of their findings proposed by Peña et al. (2010) and by Herold et al. (2008), and by data showing that prosodic and phonetic/phonotactic information are already processed by different neural networks in infancy (Dehaene-Lambertz, 2000), would be the existence of different developmental trajectories for prosody and phonetics/phonotactics, suggesting that neural immaturity affects different language levels in different ways. However, a second possibility would be that the time-lag found for prosody is due to differences in the amount of exposure to the input, given that prosody is already heard in utero. Thus, at 10 months of age full-term infants have had 10 months of extra-uterine exposure plus about 7 weeks of intra-uterine exposure, whereas preterm 10-month-olds have had only extra-uterine exposure. As phonotactic information is only heard after birth, both preterm and full-term infants only have extra-uterine exposure. A third plausible explanation would be that the difference observed is due to the fact that by losing the intra-uterine exposure to prosody, preterm infants, when they are born, have direct and simultaneous access to prosodic, phonetic and phonotactic information. This synchrony compared to the precedence of prosody in typical development might cause preterm infants to put less processing weight on prosody than on phonetics and phonotactics, triggering a delay in prosodic but not phonetic acquisition. In all cases, it appears that some of the procedures used by preterm infants to acquire language differ from what is used in typical development, or develop at a different pace. Given theories stipulating that the typical brain has a particular developmental timing and that when some subcomponents do not develop in the typical period or at the typical speed, it will have cascading effects (Karmiloff-Smith, 1997; 2009), the pattern of early development that emerges in the preterm population could eventually trigger language deficits in the school years, as has been recently suggested by Guarini and colleagues (2009; 2010).

At this point, it is important to highlight that even if no perceptual differences were found between preterm and full-term infants at 10 months, the babbling questionnaires show that there are other important differences between preterm and full-term infants. Eight of the 20 preterm 10-month-olds were still at babbling level 1, whereas none of the full-term 10-month-olds was at this level, all full-term 10-month-olds being able to produce consonant-vowel or vowel-consonant sequences. The comparison of the preterm 10-month-olds with the full-term 7-month-olds is less clear. While in our study, the preterm infants seem to have poorer babbling abilities (given that all but two of the 7-month-olds were at babbling level 2), previous research has shown that canonical sequences (which count for babbling level 2) appear between 4 and 10 months of age, with a median at 6 to 7 months (Oller, 1978; Stark, 1980; Oller, Eilers, Neal, & Cobo-Lewis, 1998). Therefore, even the 8 preterm infants still at precanonical stage 1 might fall within the normal range in terms of maturational age. Future studies on preterm infants’ babbling production will be needed to explore this issue more accurately.

Taken together, the results of the present study suggest that premature birth does not affect the acquisition of all language subcomponents in the same way in healthy preterm infants. These findings question the interpretation of previous results on prosodic acquisition in terms of maturational constraints, while underlining the possibility that different constraints apply in different ways to the acquisition of different phonological subcomponents. However, this is just one of the first steps to understand preterm infants' early speech perceptual abilities. Further studies will be needed to test populations of preterms with different characteristics (for example, extending the present study to preterms with a low weight for their GA) and larger samples of preterm infants, to define the characteristics of prematurity that impact on this acquisition. Additionally, to further explore our proposal that phonetic/phonotactic acquisition is based on duration of input experience, further studies will have to test other phonetic and phonotactic contrasts, comparing for example acquisitions based on consonants and vowels, given the results found by Figueras & Bosch (2010) and evidence that consonants and vowels have different roles in early lexical acquisition (Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet, & Butler, 2009). Lastly, the present results highlight the importance, in order to better understand the full developmental trajectory of preterm infants, of conducting further studies focused on early language acquisition to specify the subdomains (prosodic acquisition, phonetic acquisition, segmentation…) that might be affected.

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What is the role of maturation in the acquisition of phonological dependencies?
Are preterm infants sensitive to non-adjacent phonological dependencies?
Is there a delay on preterm infants' phonological development?

The results of the experiments presented in this section show:

- Preterm 10-month-old infants prefer LC over CL structures at 10 months of chronological age.
- In terms of perception, the preterm 10-month-old pattern resembles much more that of the full-term 10-month-olds (same listening age) than that of the full-term 7-month-olds (same maturational age).
- However, preterm infants seem to have a production delay, suggesting that neural immaturity affects different language levels in different ways.
- The existence of a developmental timing for phonotactic acquisition based on input experience.

  - ➔ According to these results, it seems that the LC bias is triggered by the exposure to the linguistic input and not only to maturational constrains (in line with our previous findings showing effects of manner of articulation).
  - ➔ Preterm infants are also sensitive to non-adjacent phonological dependencies.
  - ➔ No delay on the acquisition of this phonotactic property was found in the preterm population.

1.4 Studying the role of the linguistic input: The case of Japanese

> *"If we spoke a different language,*
> *we would perceive a somewhat different world."*
> *Ludwig Wittgenstein*

Another way that we tested whether the LC bias is trigger by articulatory or by perceptual constraints is to test a population learning a language in which the sequences are not more frequent than CL sequences. An analysis of the lexicon of different languages had shown that Japanese and Swahili are good candidates as languages with lexicons that do not have an LC bias (MacNeilage, et al*.,* 1999).

Thus, the theory in favor of a perceptual origin predicts the opposite CL preference for Japanese- and Swahili-learning infants, compared to the LC bias found for French. On the other hand, the theory in favor of articulatory constraints predicts that Japanese- and Swahili-learning infants will also show an LC bias, even when the lexicons of their native language show the opposite pattern.

In this section we present the results of two experiments contrasting the acquisition of non-adjacent phonological acquisitions in two populations learning two different languages, one in which there is an LC bias in the lexicon (French) and the other one in which there is no such bias (Japanese).

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Crosslinguistic phonological development: The role of the input on the development of the LC bias

Abstract

Previous studies have described the existence of a Labial-Coronal bias, that is a tendency to produce words beginning with a labial consonant followed by a coronal consonant (i.e. “bat”) rather than the opposite pattern (i.e. “tap”). This bias has initially been interpreted in terms of articulatory constraints of the human speech production system. However, different typological studies have revealed the predominance of LC sequences in the lexicons of many languages, opening the possibility that the LC bias is triggered by perceptual acquisition. The present study investigates the origins of the LC bias, testing Japanese-learning infants, a language that has been claimed to possess more CL than LC sequences, and comparing them with French-learning infants, a language showing a clear LC bias in its lexicon. First, a corpus analysis of Japanese IDS and ADS revealed the existence of an overall LC bias, except for plosive sequences in ADS, which show a CL bias. Second, the results of Experiment 1 failed to show any perceptual preference in both 7- and 10-month-old Japanese-learning infants. However, Experiment 2 revealed that 10- but not 7- month-old French-learning infants have a perceptual preference for LC sequences, which are more frequent in French, even when these sequences are produced in a foreign language (Japanese). These cross-linguistic behavioral differences reflect the differences in the properties of the lexicons of the two languages contrasted. Based on these results it appears that the emergence of the LC bias is related to exposure to a linguistic input having an LC advantage in its lexicon.

1. Introduction

Studies focusing on the analysis of the lexicons of various natural languages have revealed the existence of different phonotactic tendencies consistent crosslinguistically. For example, at the syllabic level languages privilege open (Consonant-Vowel, e.g. /ma/) over closed syllables (Vowel-Consonant, e.g. /am/; Kawasaki-Fukumori, 1992; Rousset, 2003). Languages also tend to avoid consonant clusters sharing the same manner of articulation (e.g. /pt/ or /fs/; Kawasaki-Fukumori, 1992), and they privilege Consonant-Vowel (CV) sequences sharing the same place of articulation (e,g. /be/ or /ko/ rather than /ke/ or /bo/; MacNeilage & Davis, 2000). At the intersyllabic level, languages have been shown to favor CVCV syllables having articulatory different consonants (e.g. /baga/) over reduplications (e.g. /baba/; Rochet-Capellan & Jean-Luc Schwartz, 2005). In addition, among these variegated forms, sequences starting with a labial consonant followed by a coronal consonant (e.g. /bat/) are privileged over the opposite pattern (e.g. /tap/; MacNeilage, Davis, Kinney, & Matyear, 1999; MacNeilage & Davis, 2000; Vallée, Rousset, & Boë, 2001; Gonzalez-Gomez & Nazzi, 2012). This tendency is known as the Labial-Coronal bias.

The Labial-Coronal bias was first found in early production studies. During the 50-word-stage (12-18 months), infants tend to produce 2.55 times more Labial-Coronal (LC) than Coronal-Labial (CL) structures (Ingram, 1974; Locke, 1983; MacNeilage, Davis, Kinney, & Matyear, 1999). This tendency was found in 9 out of the 10 infants tested by MacNeilage et al. (1999). The first interpretations of this bias were articulatory. Within the frame-content theory it was proposed that infants tend to begin an utterance with an easy sequence and then add complexity (MacNeilage & Davis, 2000). Since Labial-vowel (Lv) sequences are supposed to be pure frames resulting from a simple mandibular oscillation, while Coronal-vowel (Cv) sequences are fronted frames needing an additional tongue movement, infants would tend to start with a labial consonant and then add a coronal one, rather than the other way round, resulting in the LC bias.

A different articulatory explanation known as the “Labial-Coronal Chunking Hypothesis” was proposed by Sato, Vallée, Schwartz, and Rousset (2007). Their results in adult speeded articulation tasks show that when French adults produce CvCv sequences containing a labial and a coronal consonant at a fast articulatory rate, their productions tend to shift to CCv LC sequences rather than CCv CL sequences (e.g. both /bete/ and /tebe/ shift to /b'te/). Based on these results Sato and colleagues (2007) suggested that the LC bias might be explained by the higher articulatory stability of LC sequences compared with CL ones.

More recently, a perceptual explanation accounting for the LC bias has been proposed (Nazzi, Bertoncini and Bijeljac-Babic, 2009; Gonzalez-Gomez & Nazzi, 2012). This hypothesis is based on the observation of links existing between infants' preferences for specific sound sequences and their frequencies in the language. This proposal was based on the analyses of the structure of the lexicon in different languages showing that LC sequences are significantly more frequent than CL sequences. This tendency was found in English, Estonian, French, German, Hebrew, Maori, Quechua, Spanish (MacNeilage, et al., 1999), Afar, Finnish, French, Kannada, Kwalkw'ala, Navaho, Ngizim, Quechua, Sora and Yup'ik (Vallée, Rousset & Boë, 2001). According to this perceptual-based perspective, the LC bias might be a result of infants' exposure to a linguistic input containing more LC than CL sequences.

The results of two recent perceptual studies bring support to this perceptual hypothesis. Using the head-turn preference procedure (HPP), Nazzi et al. (2009) and Gonzalez-Gomez and Nazzi (2012) explored French-learning infants' preference for lists of LC or CL sequences (words or pseudo-words in French pronounced by a native female speaker). Their results showed than between 7 and 10 months of age, French-learning infants start preferring the lists corresponding to the LC sequences, the significantly more frequent phonotactic structure in French. These results are in line with prior studies showing that by 9 months of age, infants have become sensitive to the phonotactic properties of their native language, preferring legal over illegal sequences (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002), and also more frequent over less frequent phonotactically legal sequences (Jusczyk, Luce, & Charles-Luce, 1994).

Additionally, the perceptual-based explanation is supported by the results of Gonzalez-Gomez and Nazzi (in press). In a more detailed analysis of the French lexicon, the LC bias was found not to be homogenously present across consonantal classes in French: while the LC bias is clearly present for plosive and nasal sequences, this is not the case for fricative sequences. Accordingly, Gonzalez-Gomez and Nazzi (in press) tested the level of generalization at which these phonotactic acquisitions operate. In a series of experiments, 10-month-old French-learning infants' preferences for LC or CL structures in plosive, nasal and fricative sequences were evaluated. The results indicate an LC preference for plosive and nasal sequences, but a CL preference for fricative sequences, suggesting that the LC bias reflects the properties of the input and is acquired at the level of classes of consonants defined by their manner of articulation.

However, even if the results of Nazzi and collaborators (2009) and Gonzalez-Gomez & Nazzi (2012; in press) suggest that the LC bias reflects infants learning about structural regularities of the French lexicon, resulting from the exposure to the input, the possibility that this LC preference results from maturation or articulatory constraints cannot be excluded. To further investigate the influence of articulatory and perceptual constraints on the development of the LC bias, it is crucial to strengthen the evidence of the link between input and infants' emerging preferences. To do so, it is necessary to test a population learning a language having a lexicon that does not have a clear LC bias. According to MacNeilage and collaborators (1999) Japanese would constitute such a language. Their results showed not only that the Japanese lexicon does not have an LC bias, but that it tends to have the opposite pattern, that is a CL advantage. Nevertheless, these results were based on a very small sample of words (68 words extracted from a travel dictionary), calling for more thorough analyses. Employing a larger database, Tsuji, Gonzalez-Gomez, Medina, Nazzi and Mazuka (in revision) found that the adult Japanese lexicon in fact has a general LC bias. However, a more fine-grained analysis based on the findings of Gonzalez-Gomez and Nazzi (in press) revealed that this bias is not homogenously distributed, but changes across consonant classes defined by manner of articulation: the overall LC bias extended to sequences of nasals, while a CL bias was found for plosive sequences.

Therefore, exploring the processing of plosive sequences in Japanese emerges as a good test for the perceptual-based explanation of the LC bias. In this context, Tsuji and colleagues (in revision) explored Japanese adults' production and perception of plosive sequences containing a labial consonant (/p/ or /b/) and a coronal consonant (/t/ or /d/). The results revealed that Japanese adults have an LC bias in production, supporting the explanations in terms of articulatory constraints (MacNeilage & Davis, 2000; Sato, et al., 2007). However, Japanese adults did show a perceptual CL bias for these plosive sequences, showing the influence of language exposure on perceptual biases as had been previously suggested (Nazzi, et al., 2009; Gonzalez-Gomez & Nazzi, 2012; in press). Based on these results, Tsuji et al. (in revision) concluded that in adulthood the productive LC bias is due to constraints of the articulatory system, while the perceptual CL bias is based on distributional frequencies in the lexicon.

Given the claims of a universal preference for LC sequences in acquisition (MacNeilage, et al., 2000), it is of interest to investigate how the input of Japanese infants is structured and how their perceptual biases develop. Accordingly, the present study explores whether or not Japanese-learning infants develop a preference for CL plosive sequences, which are more frequent in the Japanese adult lexicon, compared to infants learning French, a language showing an LC bias for plosive sequences in its lexicon. The theory in favor of a perceptual origin predicts a CL preference for Japanese-learning infants and an opposite LC preference for French-learning infants (as already demonstrated by Nazzi, et al., 2009, and Gonzalez-Gomez & Nazzi, in press, for French-learning infants). On the other hand, the articulatory-based theory predicts that Japanese-learning infants would also show an LC bias, even when the lexicon of their native language shows the opposite pattern.

Before conducting the perceptual studies, different frequency analyses were conducted in the Japanese lexicon, both in an infant-direct speech (IDS) corpus and in an adult-direct speech (ADS) corpus. This is important given that MacNeilage and collaborators (1999) used a corpus having a very small number of words, and that Tsuji et al. (in revision) used only an adult corpus. Thus the present analyses will allow on the one hand the verification of these phonotactic properties in the Japanese lexicon. On the other hand, they will establish whether IDS shows a similar or a different pattern compared to ADS.

2. Corpus study

2.1 Input

IDS and ADS counts were obtained from the Riken Japanese Mother-Infant Conversation Corpus (R-JMICC, Mazuka, Igarashi, & Nishikawa, 2006). First, IDS analyses were made in a corpus containing the conversations of 22 mothers with their 18-to-24-month-old infants in both toy-playing and book-reading environments (collapsed for the purpose of this analysis). Second, the corpus includes a conversation of each mother with an experimenter on child-related topics (ADS), which was analyzed separately.

2.2 Analyses

Given the differences in results for different manners of articulation in the French lexicon (Gonzalez-Gomez & Nazzi, in press) and in Japanese ADS (Tsuji, et al., in revision), we conducted one analysis including all consonant manners and three analyses restricted to sequences homogeneous in terms of manner of articulation: plosives, nasals, and fricatives. The overall analysis included labials /p, b, m, f, v/ and coronals /t, d, n, s, z, ʃ, t ʃ, j, r/. The analysis of plosive sequences included labials /p, b/ and coronals /t, d/; the analysis of nasal sequences included labials /m/ and coronals /n/; the analysis of fricative sequences contained labials /f, v/ and coronals /s, z, ʃ/. Note that labial fricatives are very infrequent and, with the exception of /f/ preceding the vowel /u/, appear exclusively in recent loanwords.

Note that due to the phonotactic structure of Japanese, in which the majority of syllables have a CV structure, the analyzed sequences were mostly part of CVCV disyllables. Japanese allows CVC sequences if the second consonant is a moraic nasal, which is the only consonant in Japanese that can occur in coda position. This was, therefore, the only type of monosyllabic sequence ending in a coda consonant included in the analyses[1]. These monosyllabic sequences comprised 13.5% of the

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[1] Including moraic nasals in the frequency analysis might be regarded as somewhat unfair, because they only occur in the coda and never at the onset of a syllable; while all other consonants included in the analysis can occur in both C1 and C2 position, the moraic nasal only contributes to the counts in C2 position. We decided to include them despite this asymmetry, because this asymmetric pattern is what infants actually get in their input.

ADS, and 18.7% of the IDS sequences analyzed. However, the moraic nasal is not in itself defined for a particular place of articulation (for a discussion, cf. Vance, 1987): if it is followed by a consonant, it regressively assimilates to that consonant's place of articulation, but if it is followed by a pause or vowel, it is not possible to predict its place of articulation based on a written corpus. Therefore, we only considered CVN sequences that were immediately followed by a labial or coronal consonant and could thus unambiguously be assigned a place of articulation.

For each of the four type of sequences, four different frequency analyses were conducted: (1) token frequencies including CVC(V) sequences at any position within a word; (2) token frequencies for word-initial CVC(V) sequences only; (3) token frequencies of CVC(V) words; and (4) type frequencies of CVC(V) sequences at any position within a word.

2.3 Results and Discussion

The total number of CVCV or CVN sequences at any position within a word in the corpus was 10340 (thereof 1396 or 13.5% of CVN) in ADS and 22679 (thereof 4234 or 18.7% of CVN) in IDS. Results are shown in Table 1.

On the one hand, Japanese ADS shows an overall LC bias, which is also found for nasal and fricative sequences; but it shows a strong CL bias for plosive sequences across counts. These ADS results obtained on a rather small corpus, conform to the patterns found previously in an analysis of two larger corpora (Tsuji at al., in revision), thus backing the representativeness of this smaller corpus. On the other hand, Japanese IDS also shows an overall LC bias, which is present for all manner of articulations analyses: nasals[2], fricatives and, importantly, also plosives to the exception of the analysis restricted of CVC(V) words.

The differences between ADS and IDS with regard to the subset of plosives are remarkable given the claims of a universal preference for LC sequences in acquisition, which is mainly based on the production of plosives and nasals, and the reports on an LC bias across languages (MacNeilage, et al., 2000). With regard to

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[2] Note that the nasal LC bias reverses into a CL bias if moraic nasals are not counted (36 LC tokens, 47 CL tokens, ratio = 0.77; not shown in the table).

the only manner subset in Japanese ADS goes against previously claimed universal tendencies, IDS markedly differs from ADS and follows the pattern that is more common across languages. By contrast, an analysis of the French lexicon showed that the LC bias is consistently present both in IDS and ADS, except for fricative sequences (see Table 2 in appendix).

Table 1. Absolute frequencies of LC and CL sequences and LC to CL ratios in the RJMIIC. Ratios above 1 indicate an LC bias, ratios below 1 indicate a CL bias (marked with a rectangle).

	IDS				**ADS**			
	Overall	**Plosive**	**Nasal**	**Fricative**	**Overall**	**Plosive**	**Nasal**	**Fricative**
Token frequency								
LC	1966	183	211	8	1181	31	143	8
CL	1297	142	52	2	889	155	37	1
Ratio	1.52	1.29	4.06	4.00	1.33	0.20	3.86	8.00
Token frequency, word onset								
LC	1233	160	91	8	634	15	93	6
CL	811	136	40	0	528	122	26	1
Ratio	1.52	1.18	2.28	-	1.20	0.12	3.58	6.00
CVCV words								
LC	410	26	20	0	349	3	62	0
CL	349	96	17	0	266	61	9	0
Ratio	1.17	0.27	1.18	-	1.31	0.05	6.89	-
Type frequency								
LC	561	62	26	0	341	23	44	3
CL	380	19	17	2	283	28	19	1
Ratio	1.48	3.26	1.53	-	1.20	0.82	2.32	3.00

Taken together, these data indicate that, overall, Japanese is also an LC language, confirming the results found by Tsuji et al. (in revision). These findings are consistent for the overall analysis and for fricative and nasal sequences. However, on plosive sequences a CL bias was consistently found for ADS, and in one of the four analyses in IDS. Thus plosive sequences appear as good candidates to test differential effects of articulatory and perceptual biases, as confirmed by Tsuji et al. (in revision) testing Japanese adults.

Accordingly, we tested the preferences of 7- and 10-month-old Japanese-learning infants for LC versus CL plosive sequences. Different possible outcomes were envisaged. First, given the results showing a perceptual CL bias in Japanese adults (Tsuji et al., in revision) and given the analyses of ADS, it was predicted that Japanese-learning infants might develop a preference for CL sequences; based on previous studies with French-learning infants, this CL bias might emerge between 7 and 10 months of age. However, a second possibility based on the results on Japanese IDS is that, if infants only focus on IDS at this point of development, Japanese-learning infants might show an early LC bias, at about 10 months of age. Finally, given our contrasting findings between IDS and ADS for plosives, and since infants hear both IDS and ADS (van der Weijer, 2002; Soderstrom, 2007), a third possibility is that Japanese infants might show no clear preference at 10 months of age, but only at a later age, when infants start to be more exposed to a consistent CL-biased ADS lexicon.

3. Experiment 1

<u>*3.1 Method*</u>

3.1.1 Participants

Thirty-two infants from Japanese-speaking families were tested and their data included in the analyses: 16 7-month-olds (mean age = 7 months 19 days; range: 7 months 7 days – 28 days; 6 girls, 10 boys) and 16 10-month-olds (mean age = 10 months 12 days; range: 10 months 6 days - 29 days; 7 girls, 9 boys). The data of three additional 7-month-olds and three additional 10-month-olds were not included in the analyses due to fussiness/crying.

3.1.2 Stimuli

Twenty-four bisyllabic $C_1V_1C_2$ V_2 pseudowords were selected (see Table 3), twelve items with a labial-coronal (LC) structure and twelve items with a coronal-labial (CL) structure. Items in both lists were made up of exactly the same consonants, and the vowels were almost completely balanced across lists. Vowels had been chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the C_1V_1, V_1C_2, C_2 V_2, and $C_1V_1C_2$ V_2 sequences of phonemes according to R-JMIIC (Mazuka, et al., 2006) and the NTT frequency corpus (Amano & Kondo, 2000). The stimuli were recorded in a sound-attenuated booth by a

Japanese female native speaker with the low-high pitch contour. Two tokens of each item were selected. The duration of the LC and CL tokens was similar (327 ms vs. 318 ms, t(47)= 0.21). Four lists were created: two lists with the twelve LC items (using different tokens across lists, the order of the items in the two lists being reversed) and two lists with the twelve CL items (same manipulation). The duration of all the lists was 18.0 s. Additionally, as in Gonzalez-Gomez & Nazzi (2012), parents filled out a questionnaire (adapted from Stoel-Gammon, 1989) in order to determine infants' babbling level.

Table 3: List of Labial-Coronal and Coronal-Labial $C_1V_1C_2$ V_2 sequences used in the Experiment.

Labial-Coronal		**Coronal-Labial**	
Structure	**Pseudo-word**	**Structure**	**Pseudo-word**
$b^{v}d$	bado	**$d^{v}b$**	debi
	bida		dabe
	bode		dobe
$p^{v}t$	peto	**$t^{v}p$**	tipa
	pita		tipo
	poti		tope
$b^{v}t$	beti	**$t^{v}b$**	tabo
	beto		teba
	bite		tobi
$p^{v}d$	pade	**$d^{v}p$**	depi
	padi		dipa
	poda		dapo

3.1.3 Procedure and Apparatus

The experiment was conducted inside a sound-attenuated room, in a booth made of pegboard panels. The test booth had a red light and a loudspeaker mounted at eye level on each of the side panels and a green light mounted on the center panel. Below the center light was a video camera used to monitor infants' behavior.

A PC computer terminal, a camera, and a response box were located behind the center panel. The response box, connected to the computer, was equipped with a series of buttons. The observer, who looked at the video of the infant on the camera screen, pressed the buttons of the response box according to the direction of the infant's head, thus starting and stopping the flashing of the lights and the presentation of the sounds. The observer and the infant's caregiver listened to masking music over tight-fitting closed headphones, which prevented them from hearing the stimuli presented. Information about the duration of the head-turn was stored on the computer.

The classic version of the Head-turn Preference Procedure (HPP) was used (Jusczyk, Cutler, & Redanz, 1993a). Each infant was held on a caregiver’s lap in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented to it. Then, the red light on one of the side panels began to flash. When the infant turned in that direction, the stimulus for that trial began to play. The stimuli were delivered by the loudspeakers via an audio amplifier. Each stimulus was played to completion or stopped immediately after the infant failed to maintain the head-turn for 2 consecutive seconds. If the infant turned away from the target by 30° in any direction for less than 2s and then turned back again, the trial continued but the time spent looking away was not included in the orientation time. Thus, the maximum orientation time for a given trial was the duration of the entire speech sample.

Each session began with two musical trials, one on each side to give infants an opportunity to practice one head-turn to each side. The test phase consisted of two blocs (in each of which the two lists of each structure were presented). The order of the different lists within each block was randomized.

3.2 Results and Discussion

Mean orientation times to the LC and CL lists were calculated for each infant. Orientation times lower than 1.5 seconds were excluded from the analysis (corresponding to 1 trial for x 7-month-olds and 1 trial for x 10-month-olds) because the software used in France (Experiment 2) automatically rejects and replays such trials. Results were identical with or without these rejected trials.

The data for the Japanese-learning 7-month-olds (M_{LC} = 8.73 s, SD = 2.62 s; M_{CL} = 9.43 s, SD = 2.10 s), and for the Japanese-learning 10-month-olds (M_{LC} = 10.10 s, SD = 3.42 s; M_{CL} = 11.13 s, SD = 3.43 s), are presented in Figure 1 (left panel). A 2-way ANOVA with the between-subject factor of age (7 versus 10 months) and the within-subject factor of lexical structure (LC versus CL words) was conducted. The main effect of lexical structure and age were both marginal (F(1, 30) = 3.20, p = .08. and F(1, 30) = 3.18, p = .08, respectively). In addition the interaction between age and lexical structure was not significant F(1, 30) = .02, p = .90. Planned comparisons showed that the lexical structure effect was not significant at both 7 months, F(1, 30) = 1.39, p = .24, and 10 months, F(1, 30) = 1.83, p = .19. Longer orientation times for CL stimuli was found in only 8 of the 16 7-month-olds (p = .60, binomial test), and in 10 of the 16 10-month-olds (p = .22, binomial test). Thus, the results of Experiment 1 fail to show any perceptual preference for the structures presented in this experiment.

On the other hand, the results of the babbling questionnaire establish that all but two 7-month-olds and all 10-month-olds were at babbling level 2, the two remaining 7-month-olds being at babbling level 1. None of the infants produced sequences with varied consonants (babbling level 3), thus none produced the kinds of LC and CL structures used in our experiment.

Following the corpus analyses, we had offered three possible predictions. The lack of preference at both 7 and 10 months is compatible with the third possibility, according to which the CL preference might emerge at a later age when Japanese-learning infants start to be more exposed to ADS that is CL-biased for plosive sequences. However, because the present findings are a null result, other methodological explanations cannot be excluded. In particular, there might be an effect of the stimuli presented: It might be that the Japanese stimuli presented to the Japanese infants were for some reason less prone to induce an LC bias than the French stimuli presented to the French infants. This might be either due to properties of the language, or to idiosyncratic properties of the stimuli. In order to exclude these possibilities, a second experiment was conducted using exactly the same stimuli and procedure, but this time testing a population exposed to a language showing a clear LC bias in the lexicon, that is, French.

4. Experiment 2

4.1 Method

4.1.1 Participants

Thirty-two infants from French-speaking families were tested and their data included in the analyses: 16 7-month-olds (mean age = 7 months 9 days; range: 7

months 1 day – 23 days; 7 girls, 9 boys) and 16 10-month-olds (mean age = 10 months 12 days; range: 10 months 1 day - 26 days; 8 girls, 8 boys). The data of two additional 7-month-olds and two additional 10-month-olds were not included in the analyses due to fussiness/crying.

4.1.2 Stimuli, Procedure and Apparatus

They were the same as in Experiment 1, except for some minor apparatus differences. First the PC computer terminal, a TV screen connected to the camera, and a response box were located outside the sound-attenuated room. Second, the observer looked at the video of the infant on the TV screen. Third, if a trial lasted less than 1.5s, the trial was automatically repeated and the original orientation time was discarded.

4.2 Results and Discussion

Mean orientation times to the LC and CL lists were calculated for each infant. The data for the French-learning 7-month-olds (M_{LC} = 9.64 s, SD = 2.50 s; M_{CL} = 9.60 s, SD = 2.87 s), and for the French-learning 10-month-olds (M_{LC} = 9.17 s, SD = 2.48 s; M_{CL} = 7.20 s, SD = 2.73 s), are presented in Figure 1 (right panel). A 2-way ANOVA with the between-subject factor of age (7 versus 10 months) and the within-subject factor of lexical structure (LC versus CL words) was conducted. The effect of lexical structure was significant, F(1, 30) = 5.18, p = .03, infants having longer orientation times to LC than to CL lists. The effect of age was not significant, F(1, 30) = 3.02, p = .09. Importantly though, the interaction between age and lexical structure was significant, F(1, 30) = 4.74, p = .04, indicating that the effect of lexical structure changed with age.

Planned comparisons showed that the effect of lexical structure was not significant at 7 months, F(1, 30) = .005, p = .94, but was significant at 10 months, F(1, 30) = 9.91, p = .003. A bias for LC stimuli was found in only 8 of the 16 7-month-olds (p = .60, binomial test), but in 13 out of the 16 10-month-olds (p = .01, binomial test). These results confirmed that an LC bias emerge between 7 and 10 months of age in French-learning infants, this preference being present even with a stimuli acoustically different.

Additionally, we compared the results of Experiments 1 & 2 by conducting a 3-way ANOVA with the between-subject factors of age (7 versus 10 months) and native language (Japanese versus French), and the within-subject factor of lexical structure (LC-based versus CL-based). Importantly, the interaction between lexical structure and native language was significant, F(1, 60) = 8.16, p = .006, indicating that the effect of lexical structure changed with native language. In addition the interaction between age and native language was also significant, F(1, 60) = 6.19, p = .02. This pattern was due to the fact that orientation times tended to decrease with age in French-learning infants, while orientation times tended to increase with age in Japanese-learning infants. All other effects and interactions failed to reach significance.

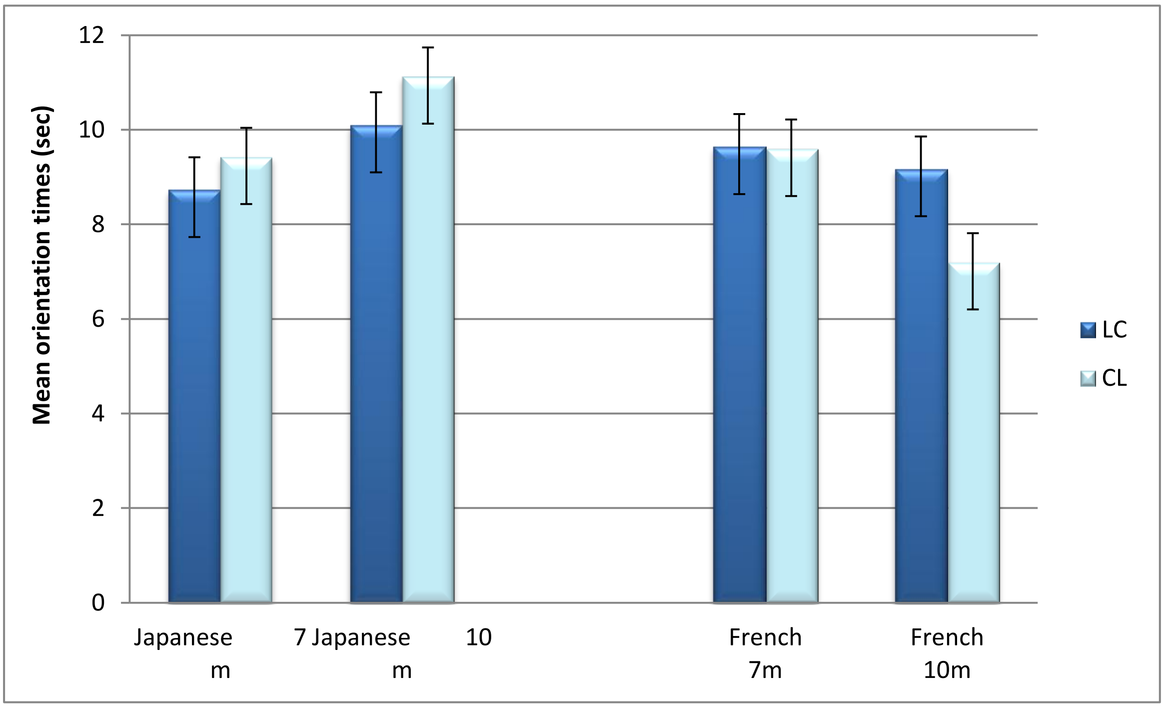

Figure 1. Mean orientation times (and standard error of the mean) to the LC and CL sequences for the 7- and 10-month-old Japanese-learning infants in Exp. 1 (left panel), and for the 7- and 10-month-old French-learning infants in Exp. 2 (right panel).

The results of the babbling questionnaire established that all but one 7-month-old and all but one 10-month-olds were at babbling level 2, the remaining 7-month-olds and the remaining 10-month-old being at babbling level 1. None of the infants produced sequences with varied consonants (babbling level 3), thus none produced the kinds of LC and CL structures used in our experiment.

5. General Discussion

The purpose of the present study was to explore the role that the linguistic input plays in the emergence of the LC bias. In the past, different studies have shown the emergence of an LC bias in early production studies (Ingram, 1974; MacNeilage, et al., 2000) and more recently at the perceptual level as well (Nazzi, et al., 2009; Gonzalez-Gomez & Nazzi, 2012). Authors have attributed this bias on one side to articulatory constraints (Ingram, 1974; MacNeilage et al., 2000; Rochet-Capellan & Schwartz, 2005), and on the other side to linguistic exposure (Nazzi et al., 2009; Gonzalez-Gomez & Nazzi, 2012). However all these studies had been conducted on languages having clear LC biases in their lexicons, preventing us from isolating the influence of the motor constraints and the perceptual input independently.

The present research explored the development of a perceptual preference for plosive sequences containing a labial and a coronal consonant in Japanese-learning infants, compared to French-learning infants. Our results revealed crosslinguistic differences in the emergence of the LC effect. For Japanese-learning infants, our studies failed to show any preference at both 7 and 10 months of age (Exp. 1). In contrast, an LC preference emerging between 7 and 10 months was found in French-learning infants (Exp. 2).

Regarding the corpus analysis conducted in this study, the Japanese ADS results showed an overall LC bias, also present for nasal and fricative sequences, but a CL bias restricted to plosive sequences. These results are consistent with the results of Tsuji and colleagues (in revision) based on a larger corpus. Interestingly, the pattern found for Japanese IDS matched with the ADS database in the overall analysis, and also for nasal and fricative sequences, which all showed an LC advantage, but the case for plosive sequences was more complex. Contrary to ADS, plosives in IDS showed an LC bias across counts, except for the count restricted to CVCV words. Thus, Japanese-learning infants are exposed to an input with an overall tendency to have more LC than CL sequences, but with a subset of consonants that show a clear CL bias in ADS, an LC bias in IDS in the token, type and word onset frequency count, and a CL bias in the CVCV count. This unclear pattern highlights a very important question about the influence that IDS and ADS have on infants' speech perception.

In fact, the null results found in Experiment 1 can be explained by the mixed frequency distribution of LC and CL sequences in the Japanese lexicon. On one side, CL plosive sequences are more frequent in ADS input, while on the other side, the advantage is in favor of LC plosive sequences in IDS. These two opposite biases seem to neutralize one another at 10 months, which might explain infants' lack of a preference at that age. Given the results of Tsuji et al. (in revision) showing that Japanese adults have a perceptual CL bias, it is likely that as infants grow up, ADS input will become more predominant, and at some point in development infants will learn that CL plosive sequences are more frequent in Japanese and consequently they will start having a preference for them. The question is, then, when infants' perceptual preferences will start shifting. Since it has been suggested that the decline in preference for IDS observed around 9 months of age (Newman & Hussain, 2006), which goes along increased language-specific abilities, is evidence for an increased role of ADS input for infant language development (Soderstrom, 2007), this CL bias for plosive sequences might emerge a few months after 10 months. Further studies on Japanese-learning infants are needed to explore this possibility.

A different pattern of results was found for French-learning infants. The results of Experiment 2 showed that 10- but not 7-month-old French-learning infants have a preference for LC sequences, the structure that is more frequent in French, even when these sequences are produced in a foreign language (Japanese). These results are in line with studies, using French stimuli, showing the existence of a perceptual LC bias in 10-month-old French-learning infants, reflecting a preference for the typical phonotactic structures of French (Nazzi, et al., 2009; Gonzalez-Gomez & Nazzi, 2012). Interestingly, the results of Experiment 2 indicate that French-learning infants' preference is not affected by the acoustic differences of the stimuli. These results contrast with the results of Tsuji and colleagues (in revision) showing that both Japanese and French adults were influenced by the language of the stimuli. Japanese adults showed a perceptual CL bias with the Japanese stimuli but not with the French ones, while French adults showed a perceptual LC bias only with the French stimuli. Two possible explanations were considered. The first one was low familiarity with the vowel categories of the non-native language. The second possibility related to the phonetic properties of plosives, which are mostly unaspirated in French (Fougeron & Smith, 1993), but weakly aspirated in Japanese (Okada, 1991). The fact that French-learning infants showed an LC bias both with French and Japanese stimuli suggests that infants’ vocalic and consonantal categories are not yet completely specified at 10 months of age.

Furthermore, the present results have implications for the interpretation of the LC bias. Classically, the effect has been explained as the result of production constraints (Ingram, 1974; MacNeilage & Davis, 2000). In contrast, Nazzi et al. (2009) and Gonzalez-Gomez & Nazzi (2012) offered a perceptual explanation. While it was unclear from previous studies whether the LC bias was triggered by articulatory constraints or by exposure to linguistic input, the latter interpretation is reinforced by the present results, showing that the emergence (or not) of the LC bias depends on exposure to a linguistic input showing such a clear bias. Thus, the present results support the interpretation that by 10 months, French-learning infants have learned some phonological dependencies present in the French lexicon, specifically, the general predominance of LC sequences over CL sequences in French, while Japanese infants did not learn such phonological dependency, given that it is not clearly present in the Japanese lexicon. However, as discussed by Nazzi et al. (2009) and Gonzalez-Gomez & Nazzi (2012), it remains possible that the labial-coronal bias involves both perceptual and production factors, since the labial-coronal bias found at 10 months is likely to reflect the perceptual acquisition of input regularities that themselves reflect articulatory constraints.

At this point, we would like to discuss a couple of issues raised by the findings of the present study that could be explored in the future. The first issue relates to the level at which these phonological regularities are acquired. Different studies have shown that infants are sensitive to natural class features and that these features constrain the acquisition of phonotactic regularities in artificial language experiments (Saffran and Thiessen, 2003; Cristia & Seidl, 2008; Cristià, Seidl, & Gerken, 2008; Seidl & Buckley, 2005), and more recently a study showed that phonotactic regularities of the native language might be learned at the level of consonantal classes defined by manner of articulation (Gonzalez-Gomez & Nazzi, in press). Given this evidence it is of interest to explore Japanese-learning infants’ acquisitions of the LC bias in a different subset of consonants, such as nasals, that show a more consistent LC bias both in IDS and in ADS. Additionally, further studies are needed to explore when in development Japanese-learning infants develop a perceptual preference for CL plosive sequences, as Tsuji and colleagues (in revision) found in adults.

To conclude, the present study revealed the existence of crosslinguistic differences in the development of the LC bias, which were predicted by the properties of the lexicon of the languages contrasted. Based on these results, it seems that exposure to linguistic input is a key factor in the emergence (or not) of the LC bias.

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Appendix

Table 2. Frequency ratios comparison of LC and CL sequences in French IDS (corpus by Karine Martel, Université de Caen Basse-Normandie) and ADS (Lexique 3 database; New, Pallier, Ferrand & Matos, 2001). Ratios above 1 indicate an LC bias, ratios below 1 indicate a CL bias.

	IDS				**ADS**			
	Plosive	**Nasal**	**Fricative**	**Overall**	**Plosive**	**Nasal**	**Fricative**	**Overall**
Token frequency								
LC	128	1	6	335	9888	3566	6326	71822
CL	35	1	1	76	5691	1063	6257	42772
Ratio	*3.67*	*1.00*	*6.00*	*4.41*	*1.74*	*3.07*	*1.01*	*1.68*
Token frequency, word onset								
LC	116	0	5	98	6039	1648	3269	45323
CL	32	0	0	10	4302	180	5240	16144
Ratio	*3.63*	-	-	*9.80*	*1.40*	*9.18*	*0.62*	*2.81*
CVCV words								
LC	25	0	5	98	526	69	725	6808
CL	8	0	0	10	295	0	329	1178
Ratio	*3.13*	-	-	*9.80*	*1.78*	-	*2.20*	*5.77*
Type frequency								
LC	15	1	3	109	1853	1015	1331	13746
CL	8	0	1	88	1269	412	784	8838
Ratio	*1.88*	-	*3.00*	*2.86*	*1.46*	*2.46*	*1.70*	*1.56*

How does the linguistic input influence phonological acquisitions? Is performance affected by acoustical differences in the stimuli used?

The results presented in this section indicate:

- The Japanese lexicon has no clear advantage for LC or CL structures.
- Japanese-learning 7- and 10-month-old infants show neither preference for LC sequences, nor a preference for CL structures.
- French-learning infants show a preference for LC sequences even when these sequences were produced in a foreign language (Japanese).
- Cross-linguistic differences were found.
- These cross-linguistic differences are predicted by the properties of the lexicon of the languages contrasted.

    - ➔ In accordance with these results, it appears that exposure to the linguistic input is a key factor in the emergence (or not) of the LC bias.
    - ➔ The performance of the French-learning infants was not affected by the acoustical differences of the stimuli

Part 2

Experimental Work

Towards the Lexical Level

2.1 Examining the link between speech perception and word segmentation

“There is only one rule for
being a good talker: learn to listen."
Christopher Morley

The third part of the present dissertation is devoted to the exploration of the link that might exist between phonological development and lexical acquisition. Throughout this section we will explore whether, and if so when, phonological acquisitions during the first year of life constrain later lexical acquisition and more specifically word segmentation.

To do so, we will exploit the fact that 10-month-old French-learning infants have already acquired a non-adjacent phonological dependencies of their native language, that is, the fact that they have learned that LC sequences are much more frequent in French than CL ones, as has been shown in the second part of this dissertation.

The following paper presents two experiments exploring infants’ ability to segment words having a high phonotactic frequency (LC) versus words having a low phonotactic frequency (CL). These sequences are ideal to test the relation between phonotactic knowledge and word segmentation for two reasons. First there is evidence showing that infants are sensitive to these kinds of sequences. Second these sequences were found to be good clues to word boundaries.

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Nayeli Gonzalez-Gomez & Thierry Nazzi (Submitted to Journal of Speech, language, and Hearing Research)

Effects of prior phonotactic knowledge on infant word segmentation: The case of non-adjacent dependencies

Abstract

Purpose: In the present study, we explore whether French-learning infants use non-adjacent phonotactic regularities in their native language, which they learn between 7 and 10 months of age, to segment words from fluent speech.

Method: Two groups of 20 French-learning infants were tested using the head-turn preference procedure at 10 and 13 months of age. In Experiment 1, infants were familiarized with two passages: one containing a target word with a frequent non-adjacent phonotactic structure and the other passage containing a target word with an infrequent non-adjacent phonotactic structure in French. During the test phase infants were presented with 4 word lists: two containing the target words presented during familiarization and two other control words with the same phonotactic structure. In Experiment 2, infants' ability to segment words with the infrequent phonotactic structure was tested in isolation.

Results: Ten- and 13-month-olds were able to segment words with the frequent phonotactic structure, but it is only by 13 months, and only under the circumstances of Experiment 2, that infants could segment words with the infrequent phonotactic structure.

Conclusions: Our results provide the first piece of evidence showing that infant word segmentation is influenced by prior non-adjacent phonotactic knowledge.

Running head: Effect of non-adjacent phonotactics on infant word segmentation

Keywords: language acquisition, word segmentation, phonotactics, labial-coronal bias, French.

Introduction

From birth, infants are immersed in speech, hearing thousands of utterances that do not include systematic marks of where word boundaries are. Therefore, in order to learn the words of their native language, infants have to solve a very challenging task, that is, they have to discover what is and what is not a word-like unit. Years of research have shown that to start finding word boundaries, infants exploit different phonological regularities of their language very early in life. The present study will contribute to this research by exploring infants' use of non-adjacent phonotactic knowledge.

A first cue that has been found to play a particularly important role for word segmentation is transitional probabilities (TPs), that is the normalized version of the probability of event Y given event X (TP (Y/X) = frequency of XY/ frequency of X), which is used as early as 6 months of age (Saffran, Aslin, & Newport, 1996; Johnson & Tyler, 2010; Mersad & Nazzi, 2012). A second important cue relates to prosodic regularities, and more precisely rhythmic units like the trochaic unit for stressed-based languages such as English or Dutch (Echols, Crowhurst, & Childers, 1997; Jusczyk, Houston, & Newsome, 1999; Jusczyk, Kuijpers, Coolen, & Cutler, 2000; Kooijman, Hagoort, & Cutler, 2009; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel, & Jusczyk, 2005), or the syllabic unit for syllable-based languages such as French (Goyet, de Schonen, & Nazzi, 2010; Mersad, Goyet, & Nazzi, 2010/2011; Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006; Polka & Sundara, 2012), which are used for segmentation by 8 months of age at the latest. Third, allophonic variations, that is the fact that some phonemes are pronounced in a different way depending on their position in the word, has also been found to impact word segmentation by 10.5 months of age (Jusczyk, Hohne, & Baumann, 1999).

A fourth cue to early word segmentation, which is explored in the present study, is phonotactic knowledge, which refers to regularities regarding the legality or frequency of sequences of phonemes that are allowed/found in the words of a given language. In a first study, Mattys, Jusczyk, Luce and Morgan (1999) found that at 9 months infants are already sensitive to the way in which phonotactic sequences (cross-syllabic C*C clusters) typically align with word boundaries in their native language, which affects their preferences for bisyllabic sequences. In a subsequent study, Mattys and Jusczyk (2001a) established that the probability of appearance of clusters within words or at word boundaries also affects the way they segment words out of fluent speech. Their results establish a segmentation advantage for words presented in a phonotactic context in which they are surrounded by high-probability between-words clusters, suggesting that 9-month-old infants use adjacent phonotactic information to find word boundaries.

The above studies thus establish that prior phonotactic knowledge influences segmentation by as early as 9 months in English-learning infants. The present study will go beyond these findings by extending the evidence to infants learning another language, French. Second, and more importantly, it will explore whether infants can use not only adjacent phonotactics as demonstrated by Mattys and colleagues, but also non-adjacent dependencies. Demonstrating such an extension would be important because languages instantiate both adjacent and non-adjacent dependencies[1]. At the phonological level, research on adults has established that a non-adjacent cue, vowel harmony, can be used for segmentation by adults (Suomi, McQueen & Cutler, 1997; Vroomen, Tuomainen & de Gelder, 1998). Though never investigated before, the possibility of finding an effect of non-adjacent dependencies on early word segmentation is rendered likely by recent findings having shown infants' acquisition of non-adjacent phonotactic knowledge at the same age as they acquire adjacent knowledge.

Regarding adjacent phonotactic dependencies, research has established that they are acquired early, as evidenced by the fact that between 6 and 9 months of age, infants start preferring the phonotactic patterns of their native language. English- and Dutch-learning 9-month-olds listened longer to phonemic sequences legal in their native language than to illegal ones (Jusczyk, et al., 1993; Friederici & Wessels, 1993), while 6-month-olds do not have a preference. A similar

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[1] Non-adjacent dependencies are an important feature of natural languages, given that languages make an extensive use of non-adjacent/distant dependencies, both at the phonological level (e.g., vowel harmony) but also at the syntactic/morphosyntactic level (e.g., subject-verb agreement, number agreement…; c.f. Gonzalez-Gomez & Nazzi, 2012 for a more detailed discussion of these issues).

developmental pattern was found for Spanish/Catalan bilingual infants (Sebastián-Gallés & Bosch, 2002). Infants learning various languages therefore become sensitive to the legality of adjacent sound sequences in their native language by 9/10 months. Furthermore, they have also been found to become sensitive to the relative probability of occurrence of adjacent sound sequences at the same age, 9-month-old English-learning infants preferring to listen to high-probability than low-probability phonotactic sequences (Jusczyk, Luce, & Charles-Luce, 1994). All these finding establish that infants have become sensitive to the phonotactic patterns of their native language occurring between adjacent elements by 10 months of age.

More recently, two studies have shown that infants also become sensitive to non-adjacent phonological dependencies by 10 months of age (Nazzi, et al., 2009a; Gonzalez-Gomez & Nazzi, 2012). In French, the language of the infants tested in those studies, Labial-Coronal (LC) words (that is, words starting with a labial consonant followed by a coronal consonant, such as “bite”) are much more frequent than words with the opposite Coronal-Labial (CL) pattern (that is, words starting with a coronal consonant followed by a labial consonant, such as “tipi;” MacNeilage & Davis, 2000; Vallée, Rousset, & Boë, 2001; Gonzalez-Gomez & Nazzi, 2012). These perceptual studies found that 6, but not 10-month-old infants prefer to listen to LC words than to CL words. These results were taken as evidence of non-adjacent phonotactic acquisition, since the LC bias is considered a non-adjacent phonotactic dependency, given that it involves a relation between two consonants separated by a vowel. The fact that infants were reacting to the relative position of the non-adjacent consonants is further supported by the fact that in Gonzalez-Gomez and Nazzi (2012) all the adjacent frequencies of the stimuli were fully controlled, leaving only an overall non-adjacent frequency advantage for LC sequences. Moreover, Gonzalez-Gomez and Nazzi (2012) conducted two control experiments that showed that the LC preference found at 10 months was not due to a Labial word-initial bias or a Coronal word-final bias.

Following the above findings, the present study explores whether infants can use their non-adjacent phonotactic knowledge to find word forms in fluent speech. Before presenting the experiments that were conducted to address this issue, we present the results of an analysis that we conducted on a corpus of speech addressed to infants (corpus by Karine Martel, Université de Caen Basse-Normandie) in order to verify the distribution in infants' input of LC and CL sequences, and how they relate to words and word boundaries. The corpus contains the recordings of 10 mothers interacting with their infants (mean age = 7 months 24 days; range: 5 months 8 days – 10 months 22 days; 5 girls, 5 boys). Recordings were made at their home while the mother was interacting with the infant using toys brought by the experimenter. Recording duration varies from one dyad to another one ($\text{Mean}_{\text{duration}}$ = 16 minutes, range = 9 minutes – 24 minutes). The corpus contains 6673 word tokens, corresponding to 2524 utterances from the 10 mothers who participated in the recordings. In that corpus, we counted the number of times that LC and CL sequences appear, in either intrasyllabic or intersyllabic position, within or between words.

Table 1. Total number of LC and CL sequences observed within words (Left panel) and between words (Right panel) in the Martel corpus.

	Within Words			Between Words[3]
	Intersyllable	Intrasyllable	Total	Intersyllable
Labial-Coronal	240	97	337	237
Coronal-Labial	67	9	76	750

A first way of analyzing the results (c.f. Table 1) is to look at the types of sequences that occur more frequently within words and across words (column analysis). This comparison shows that within words, LC sequences are predominant, constituting 78% of intersyllabic sequences, and 92% of intrasyllabic sequences. On the other hand, 76% of the sequences between words are CL sequences. Therefore, LC sequences appear to have high within-word frequencies and low between-word frequencies, while CL sequences have high between-word frequencies, and low within-word frequencies. From these patterns, it appears that word-like units are likely to be LC sequences, while word boundaries are more likely to correspond to CL sequences. A second way to analyze the data presented in Table 1 is to determine whether finding an LC or CL sequence would allow predicting whether that sequence is part of a word, or spans a word

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[3] No intrasyllabic between-word sequences were found.

boundary (row analysis). These comparisons show that 59% of LC sequences appear within words, while 91% of CL sequences appear at word boundaries. Therefore, if infants assumed that every LC sequence appears within a word, they would be right almost 60% of the time, and if they assumed that every CL sequence marks a word boundary, they would be right more than 90% of the time.

In light of these elements, the present study explores whether infants are using LC and CL sequences as predictors of word forms and word boundaries. Experiment 1 was conducted to compare French-learning infants' ability to segment from fluent speech words with high within-word frequencies and low between-word frequencies (LC words) and words with low within-word frequencies and high between-word frequencies (CL words). Based on the literature on the impact of adjacent phonotactic knowledge on early word segmentation, we predicted better performance for LC words. Two groups of infants were tested, at 7 and 10 months of age, using the procedure set up by Jusczyk and Aslin (1995) in which infants are familiarized with passages containing target words, and then tested on their recognition of these words.

Experiment 1

Method

Participants. Forty infants from French-speaking families were tested: Twenty 10-month-olds (mean age = 10 months 15 days; range: 10 months 5 days - 24 days; 8 girls, 12 boys) and Twenty 13-month-olds (mean age = 13 months 18 days; range: 13 months 6 days - 28 days; 12 girls, 8 boys). The data of three additional 10-month-olds and two additional 13-month-olds were not included in the analyses due to fussiness/crying (n = 5).

Stimuli. Eight monosyllabic Cons1Vow1Cons2 pseudo-words were selected, combining labial consonants p and b, and coronal consonants t and d: four items with a labial-coronal (LC) structure (1 bVd: /bɔd/; 1 pVt: /pœt/; 1 bVt: /but/; and 1 pVd: /pid/) and four items with a coronal-labial (CL) structure (1 dVb: /dɔb/; 1 tVp: /tœp/; 1 tVb: /tub/; and 1 dVp: /dip/). Items in both lists were made up of exactly the same consonants and vowels. As in Gonzalez-Gomez and Nazzi (2012), vowels were chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the Cons1Vow1, Vow1Cons2 and Cons1Vow1Cons2 sequences of phonemes according to the Lexique 3 database (New, Pallier, Ferrand & Matos, 2001), ensuring that infants react to the overall relative position of the non-adjacent consonants.

Four different passages containing eight sentences were used. Each passage was associated both to an LC sequence and to a CL sequence across conditions.

All the stimuli were recorded in a sound-attenuated booth by a French female native speaker who was naive to the hypotheses of the study. Twenty different tokens of each word were selected to create eight word lists: four LC lists (one for each of the four LC words) and four CL lists (one for each of the four CL words). The duration of all the word lists and passages was 20.00 s.

Procedure and Apparatus. The experiment was conducted inside a sound-attenuated room, in a booth made of pegboard panels (bottom part) and a white curtain (top part). The test booth had a red light and a loudspeaker (SONY xs-F1722) mounted at eye level on each of the side panels and a green light mounted on the center panel. Below the center light was a video camera used to monitor infants’ behavior.

A PC computer (Dell Optiplex), a TV screen connected to the camera, and a response box were located outside the sound-attenuated room. The response box, connected to the computer, was equipped with a series of buttons. The observer, who looked at the video of the infant on the TV screen to monitor infant’s looking behavior, pressed the buttons of the response box according to the direction of the infant's head, thus starting and stopping the flashing of the lights and the presentation of the sounds. The observer and the infant's caregiver wore earplugs and listened to masking music over tight-fitting closed headphones, which prevented them from hearing the stimuli presented.

We used the version of the Head-turn Preference Procedure (HPP) set up by Jusczyk and Aslin (1995). Each infant was held on a caregiver’s lap in the center of the test booth. Each trial began with the green light on the center panel blinking until the infant had oriented to it. Then, the red light on one of the side panels began to flash. When the infant turned in that direction, the stimulus for that trial began to play. The stimuli were delivered by the loudspeakers via an audio amplifier (Marantz PM4000). Each stimulus was played to completion or stopped immediately after the infant failed to maintain the head-turn for 2 consecutive seconds. If the infant turned away from the target by 30° in any direction for less than 2s and then turned back again, the trial continued but the time spent looking away (when the experimenter released the buttons of the response box) was automatically subtracted from the orientation time by the program. Thus, the maximum orientation time for a given trial was the duration of the entire speech sample. If a trial lasted less than 1.5 s, the trial was repeated and the original orientation time was discarded. Information about the duration of the head-turn was stored on the computer.

Each experimental session began with a familiarization phase containing two different passages, one with an LC target and one with a CL target. Within each passage each target word was repeated 8 times. Passages were presented in random order until infants accumulated 30 s of listening time to each. The test phase consisted of two test blocks, each corresponding to the presentation of four different lists: Two lists containing the two words presented during the familiarization phase (Familiar LC, Familiar CL) and two lists containing two novel/control words (Control LC or Control CL). The order of presentation of the 4 lists within each block was randomized.

Design. In each age group, infants were divided in four subgroups and familiarized with one of four possible pair of passages (/but/-/dip/, /pid/-/tub/, /pœt/-/dɔb/, and /bɔd/-/tœp/). Each infant was familiarized with two passages: one containing an LC target word and the second one with a CL target word. Each word was used an equal amount of time as target and control across infants.

Results and Discussion

Orientation times to the familiar and the control lists were calculated for each infant and averaged across infants within each group: 10-month-olds ($M_{Familiar}$ = 7.57 s, SD = 1.62 s; $M_{Control}$ = 6.24 s, SD = 1.65) and 13-month-olds ($M_{Familiar}$ = 9.10 s, SD = 3.03 s; $M_{Control}$ = 6.01 s, SD = 2.01; c.f. Figure 1). A 3-way ANOVA with the between-subject factor of age (10 months versus 13 months) and the within-subject factors of familiarity (familiar versus control) and lexical structure (LC versus CL) was conducted. The effect of familiarity was significant, F (1, 76) = 27.84, p < .001, ηp^2 = .27, infants having longer orientation times to familiar than to control lists. The effect of lexical structure was also significant, F(1, 76) = 41.85, p = .05, ηp^2 = .05, infants having longer orientation times to LC than to CL lists. In addition, the interaction between familiarity and age was significant, F(1, 76) = 4.44, p = .04, ηp^2 = .06. This was due to the fact that the difference between familiar and control words was greater for the 13-month-olds (3.10 s) than for the 10-month-olds (1.23 s). More importantly, the interaction between familiarity and lexical structure was also significant, F(1, 76) = 13.24, p < .001, ηp^2 = .15, suggesting that the effect of familiarity was different for the two lexical structures. Planned comparisons showed that the familiarity effect was not significant in the CL condition at both ages (10-month-olds, F(1, 76) = .25, p = .61; 13-month-olds, F(1, 76) = 1.27, p = .26) while the effect was significant in the LC condition at both ages (10-month-olds, F(1, 76) = 7.07, p = .009, d = .84; 13-month-olds, F(1, 76) = 39.15, p < .001, d = 1.56). All other effects and interactions failed to reach significance.

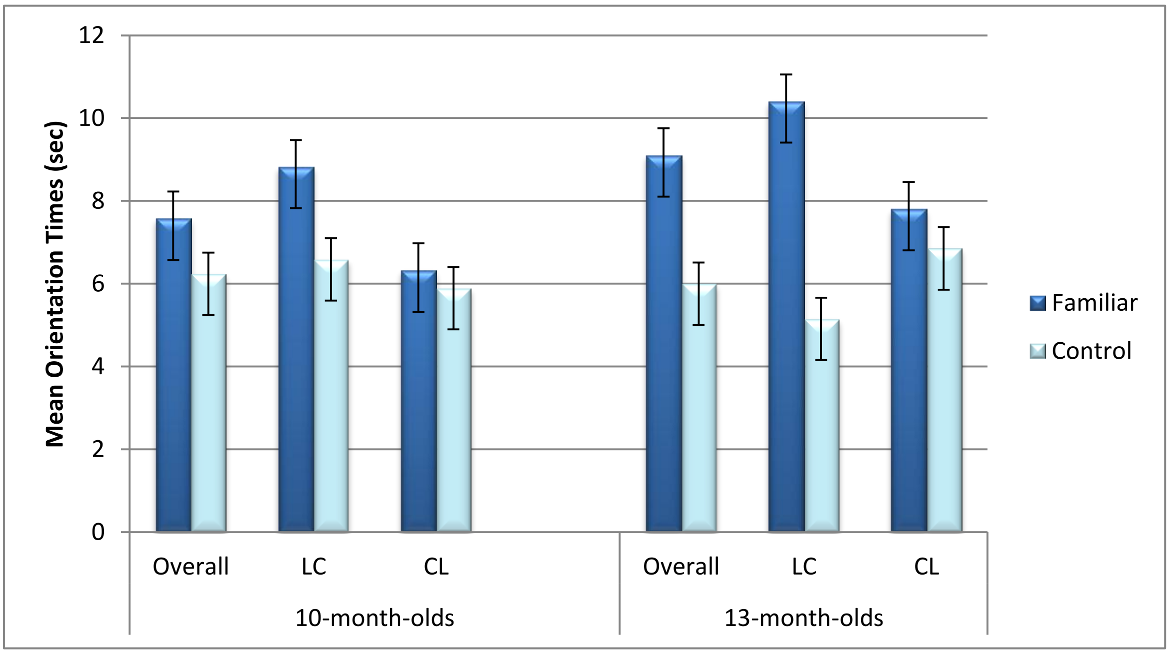

Figure 1. Mean orientation times (and SE) to the Familiar versus Control words for both conditions averaged together (overall), the LC condition and the CL condition. Left panel: 10-month-olds; right panel: 13-month-olds.

Experiment 1 shows that 10- and 13-month-old infants are able to segment the LC words, but fails to provide evidence that they are segmenting the CL words. It is important to remember that in French, LC sequences are much more frequent word-internally than CL sequences, and that 10-month-olds prefer to listen to lists of LC words over CL words (Nazzi, et al., 2009a; Gonzalez-Gomez & Nazzi, 2012). Therefore, there are at least two possible explanations to the failure in the CL condition. The first is that 10 and 13-month-olds are not able to segment CL sequences given that these structures have a low within-word frequency and a high between-word frequency, a pattern associated to word boundaries. A second possibility is that 10- and 13-month-old French infants are actually able to segment the CL sequences, but they were not able to show this in Experiment 1 due to a competition effect, given that LC and CL structures were both presented during the test. As a result, the most familiar LC structures might have attracted infants' attention, interfering with the processing of the CL ones. This possibility is suggested by the overall longer orientation times to the LC words found in the test phase.

In order to evaluate these possibilities, Experiment 2 was run, in which only the CL stimuli of Experiment 1 were used. This manipulation removed the potential competition effect of presenting LC and CL words together. If 10- and 13-month-old infants were able to segment the CL sequences, but there was a competition effect in the test phase, then 10 and 13-month-olds should show evidence of segmenting CL sequences in Experiment 2. By contrast, if they were not able to segment the CL sequences, no such effect should be found in Experiment 2 either.

Experiment 2

Method

Participants. Forty infants from French-speaking families were tested: 20 10-month-olds (mean age = 10 months 10 days; range: 10 months 2 days – 24 days; 10 girls, 10 boys) and 20 13-month-olds (mean age = 13 months 11 days; range: 13 months 1 days - 25 days; 11 girls, 9 boys). The data of three additional 10-

month-olds and two additional 13-month-olds were not included in the analyses due to fussiness/crying (n = 5).

Stimuli. All the CL stimuli from Experiment 1 were used.

Procedure and Apparatus. Same as in Experiment 1, except that infants only heard CL targets.

Design. In each age group, half of the infants were familiarized with passages containing the target words /tub/ and /dɔb/, and the other half with passages containing the target words /dip/ and /tœp/.

Results and Discussion

Mean orientation times to the Familiar and Control lists were calculated for each infant. The data for the 10-month-olds ($M_{Familiar}$ = 7.29 s, SD = 2.86 s; $M_{Control}$ = 7.72 s, SD = 3.39), and for the 13-month-olds ($M_{Familiar}$ = 7.23 s, SD = 2.74 s; $M_{Control}$ = 5.61 s, SD = 1.80 s), are presented in Figure 2. A 2-way ANOVA with the between-subject factor of age (10 versus 13 months) and the within-subject factor of Familiarity (Familiar versus Control words) was conducted. The familiarity effect was not significant, F(1, 38) = 1.68, p = .20. The effect of age also failed to reach significance, F(1, 38) = 2.14, p = .15. However, the interaction between age and familiarity was significant, F(1, 38) = 4.98, p = .03, ηp^2 = .11, indicating that the effect of familiarity changed with age. Planned comparisons showed that the lexical structure effect was not significant at 10 months, F(1, 38) = .43, p = .51, but was significant at 13 months, F(1, 38) = 6.23, p = .01, d = .69. These results again fail to show that 10-month-old infants are able to segment CL sequences.

Taken together with the results of Experiment 1, the present results establish that 10-month-old infants are not able to segment the low within-word frequency and high between-word frequency CL words. Therefore, it appears that 10-month-olds' failure in Experiment 1 was not due to a competition effect in the test phase. However, by 13 months, infants are able to segment the CL words. Therefore, it seems that the failure of the 13-month-olds with CL words in Experiment 1 was due to a competition effect related to the presentation of both LC and CL words. Hence, our findings reveal developmental changes between 10 and 13 months of age, indicating that during this period infants become able to segment words having high between-word frequencies and a low within-word frequencies.

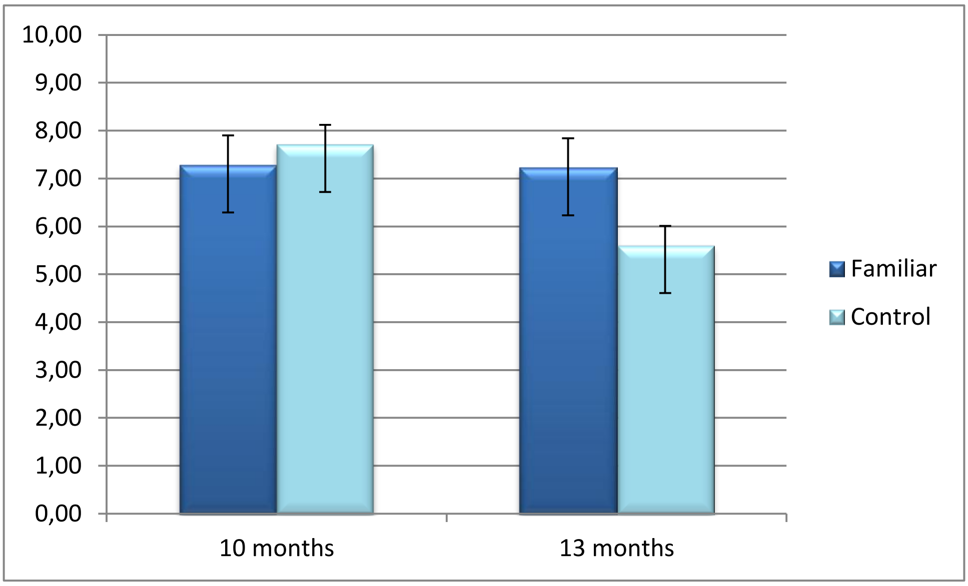

Figure 2. Mean orientation times (and SE) to the Familiar versus Control stimuli for the 10- and 13-month-olds, using only CL stimuli (Exp. 2).

General Discussion

The goal of the present study was to explore how prior knowledge of the probability of non-adjacent sound sequences impacts infants' word segmentation. To explore this issue, we investigated when French-learning infants start segmenting Labial-Coronal (LC) sequences that are very frequent word-internally compared to Coronal-Labial (CL) sequences that are less frequent word-internally in French. The results of two experiments show that infants are able to segment LC sequences at least by 10 months of age, but that they are not able to segment the opposite CL pattern until a few months later, by 13 months of age. The present study brings the first piece of evidence showing that infant word segmentation is affected by the relative frequency of non-adjacent phonological dependencies. These results confirm that infants are sensitive to non-adjacent phonological dependencies as previously shown (Nazzi, et al., 2009a; Gonzalez-Gomez & Nazzi, 2012). More importantly, they show that non-adjacent phonological dependencies can be useful for processes related to early lexical acquisition.

There are at least two factors that might explain our finding that LC words are easier to segment than CL words for these infants. The first one is that LC sequences have a frequent phonotactic structure. Since it has been shown that 10-month-old infants have a preference for these structures (Nazzi, et al., 2009a; Gonzalez-Gomez & Nazzi, 2012), it is possible that structure typicality played a role in the recognition of these structures. As argued by Jusczyk et al. (1994), frequent phonotactic structures are likely to be more easily recognized and consequently more easily segmented. The second factor is revealed by our corpus analysis, showing that LC sequences are not only more frequent in the French lexicon (Gonzalez-Gomez & Nazzi, 2012; Vallée et al., 2001; MacNeilage & Davis, 2000), but they also have a high within-word frequency and a low between-word frequency, a frequency pattern associated to word-like units.

The two factors that facilitated the segmentation of the LC words can also explain our findings that CL words were not segmented by 10 but only by 13 months of age. First, CL sequences are much less frequent word-internally that LC ones. Second, CL sequences have low within-word frequencies and high between-word frequencies, which is associated with word boundaries. It is important to remember that in the Martel corpus, 90% of CL sequences were found between words. If 10-month-olds have discovered that CL sequences mostly occur at word boundaries, it is possible that they treat CL sequences as being part of two different words, thus mis-segmenting CL words. This effect would be transitory, since by 13 months, infants are able to segment the CL words. This possibility of transitory mis-segmentation is in line with Jusczyk, Houston, and Newsome (1999) results showing that 7.5 month-old English-learning infants are able to segment words containing a strong/weak stress pattern, which is the most common pattern in their native language, but that they mis-segment words having a weak/strong stress pattern, to match it up with the common strong/weak pattern (i.e. “guitar is” segmented as “taris”). Three months later, at 10.5 months, infants are also able to segment weak/strong words, probably by relying on other segmentation cues. The pattern found in our study on phonotactics is thus similar to the pattern that was found in the Jusczyk et al. (1999) study on prosody.

While mis-segmentation of the CL words is a possibility, the structure of our stimuli however makes this possibility unlikely. First, our targets are monosyllabic

CVC words, and syllables have often been thought as good segmentation units (Mehler, Dupoux, & Segui, 1990; Jusczyk, Goodman, & Baumann, 1999; Eimas, 1997), in particular for French (Goyet, et al., 2010; Nazzi, et al., 2006). Second, in our study target words were followed by a consonant-initial word in 78% of the sentences (i.e. /sɛʀtɛ̃ tub sɔ̃ bjɛ̃ meʀite/). As a consequence, mis-segmenting the CL sequences by placing a word boundary between the two consonants would produce illegal or very rare within-word clusters in French more than 50% of the times (i.e., /sɛʀtɛ̃tu bsɔ̃/). Since Mattys and colleagues (1999; 2001a) have shown that infants are already sensitive to cluster probabilities at word boundaries by 9 months of age, in both onset and coda positions, such segmentation is unlikely to have happened. Therefore, a further possibility is that the presence of conflicting cues led to the non-segmentation of the portion of speech around the CL words. Further research is needed to explore these and other possible explanations.

In summary, the findings of the present study extend the evidence in the literature showing that English-learning infants are able to use phonotactic cues to find words in fluent speech (Mattys, et al., 1999, Mattys, & Jusczyk, 2001a) to French-learning infants. Moreover, our results extend the existing evidence about the influence that prior phonotactic knowledge on word segmentation, from the use of adjacent regularities to the use of non-adjacent dependencies. They also provide further evidence of a link between early speech perception/phonological acquisition and word segmentation, as previously shown for prosodic cues (phonological acquisition: Jusczyk, Cutler & Redanz, 1993; word segmentation: Jusczyk, Houston & Newsome, 1999), allophonic cues (phonological acquisition: Hohne & Jusczyk, 1994; word segmentation: Jusczyk, Hohne, & Baumann, 1999; Mattys & Jusczyk, 2001b), and adjacent phonotactic cues (phonological acquisition: Jusczyk, et al., 1993; word segmentation: Mattys, et al., 1999; Mattys & Jusczyk, 2001a) . In our case, we show for the first time that the non-adjacent phonological dependencies of their native language that French-learning infants have learned by 10 months of age (Nazzi, et al., 2009a; Gonzalez-Gomez, & Nazzi, 2012) are used at the same age to find word-like units in the speech stream. Future studies will have to explore the generality of this finding to other non-adjacent dependencies. One place to start would be to test the acquisition and use for segmentation of non-adjacent vowel dependencies, given recent evidence showing that consonantal information is more important that vocalic information at the lexical level (Nespor, et al., 2003; Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet & Butler, 2009b, Bonatti, et al., 2005). In conclusion, the present study provides evidence showing that prior phonotactic knowledge can constrain processes involved in later lexical acquisition, such as the segmentation of words from speech stream, even when it involves a non-adjacent dependency.

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Appendix

Phrases used in the Experiment 1 & 2*

Condition 1

	LC		CL*
1	Vos boute broutent dans le prè	1	Ne bois pas au dipe des canettes
2	Les filles raffolent de boute crapuleux	2	Certains dipe se pêchent au harpon
3	Ton boute de douche est cassé	3	Eviter de croire les dipe spirituels
4	J'ai remplis notre boute de cerises	4	Quatre dipe sèchent dans une cave
5	Quelques boute rouges sont froissés	5	Depuis des mois, il a un dipe phobique
6	Les meubles sont rangés dans un boute scellé	6	Cinq dipe se trouvent sur la table
7	Notre boute à convaincu l'assemblé	7	J'admire la nuit cet étrange dipe gris
8	J'ai besoin de plus de boute en hiver	8	Le dipe est une qualité qui se fait rare

Condition 2

	LC		CL*
1	Trop de pide abrutit les enfants	1	Hier soir, trois toube ont sauté la clôture
2	J'ai marché sur un pide de bouteille	2	Quelques toube sont dits sur cet homme
3	Quelques pide sont dans cette classe	3	Je dois changer ce toube usé
4	Les veaux boivent aux pide de leur mères	4	Certains toube sont recyclables
5	J'habite près des pide des arts	5	L'homme s'assied sur le toube brûlant
6	J'ai acheté trois pide en croute	6	Un fin toube de vase est visible dans l'eau
7	Le pide lui sera offert à noël	7	Cette équipe rédige quelques toube très concis
8	Il existe quatre pide dans la région	8	Certains toube sont bien mérités

Condition 3

	LC		CL*
1	Hier soir, trois bode ont sauté la clôture	1	Trop de teupe abrutit les enfants
2	Quelques bode sont dits sur cet homme	2	J'ai marché sur un teupe de bouteille
3	Je dois changer ce bode usé	3	Quelques teupe sont dans cette classe
4	Certains bode sont recyclables	4	Les veaux boivent aux teupe de leur mères
5	L'homme s'assied sur le bode brûlant	5	J'habite près des teupe des arts
6	Un fin bode de vase est visible dans l'eau	6	J'ai acheté trois teupe en croute
7	Cette équipe rédige quelques bode très concis	7	Le teupe lui sera offert à noël
8	Certains bode sont bien mérités	8	Il existe quatre teupe dans la région

Condition 4

	LC		CL*
1	Ne bois pas au peute des canettes	1	Vos dobe broutent dans le prè
2	Certains peute se pêchent au harpon	2	Les filles raffolent de dobe crapuleux
3	Eviter de croire les peute spirituels	3	Ton dobe de douche est cassé
4	Quatre peute sèchent dans une cave	4	J'ai remplis notre dobe de cerises
5	Depuis des mois, il a un peute phobique	5	Quelques dobe rouges sont froissés
6	Cinq peute se trouvent sur la table	6	Les meubles sont rangés dans un dobe scellé
7	J'admire la nuit cet étrange peute gris	7	Notre dobe a convaincu l'assemblé
8	Le peute est une qualité qui se fait rare	8	J'ai besoin de plus de dobe en hiver

Does phonotactical prior knowledge can influence word segmentation?

The results presented in this section indicate:

- 10-month-old French-learning infants are able to segment LC pseudo-words but not CL ones.
- CL pseudo-words are segmented later, by 13 months of age
- LC words are easier to segment than CL words, as attested by the fact that they are segmented at an earlier age.

➔ Based on these results and other previous results we can conclude that prior phonotactic knowledge can constrain later lexical acquisition, such as the segmentation of words from speech stream, even when it involves a non-adjacent dependency.

2.2 Investigating the link between speech perception and word learning

“A word is not a crystal, transparent
and unchanged, it is the skin of a living thought
and may vary greatly in color and content according
to the circumstances and the time in which it is used.“
Oliver Wendell Holmes

This section further explores the link that exists between phonological development and lexical acquisition. However, this part is focused on the relation existing between phonological acquisitions during the first year of life and later word learning during the second year of life.

The next paper presents a study exploring this question. Taking advantage of the fact that 10-month-old French-learning infants show an LC bias, we tested infants’ ability to learn novel LC and CL words during a word learning task.

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A “bat” is easier to learn than a “tab”: Effects of relative phonotactic frequency on infant word learning

Abstract

Many studies have shown that during the first year of life infants start learning the prosodic, phonetic and phonotactic properties of their native language. In parallel infants start associating sound sequences with meaning representations. However, the question of how these two processes interact remains largely unknown. The current study explores whether (and if, when) the relative phonotactic probability of a sound sequence in the native language has an impact on infants’ word learning. We exploit the fact that Labial-Coronal (LC) words are more frequent than Coronal-Labial (CL) words in French, and that French-learning infants prefer LC over CL sequences at 10 months of age, to explore the possibility that LC structures might be learned more easily and thus at an earlier age than CL structures. Eye movements of French-learning 14- and 16-month-olds were recorded while they watched animated cartoons in a word learning task. The experiment involved four trials testing LC sequences and four trials testing CL sequences. Analyses on the proportion of target looking revealed that 16-month-olds were able to learn both the LC and the CL words. In contrast, the results showed that the 14-month-olds were only able to learn LC words, which are the words with the more frequent phonotactic pattern. The present results provide evidence that infants’ knowledge of their native language phonotactic patterns influences their word learning: Words with a frequent phonotactic structure could be acquired at an earlier age than those with a lower probability. Developmental changes are discussed and integrated with previous findings.

Keywords: language acquisition, word learning, phonotactic constrains, labial-coronal bias,

1. Introduction

During the past decades a large number of studies have focused on exploring how infants' speech perception abilities become tuned to their native language on the one hand, and on studying how infants start associating sound sequences with meaning representations, that is learning words, on the other hand. However, very little is known about how these two processes interact. The present study aims to investigate a potential link between perceptual acquisition and early word learning. More specifically, it explores whether (and if, when) the relative phonotactic probability of a sound sequence in the native language has an impact on infants' word learning.

Before infants are able to learn words, they have to deal with a huge amount of information in order to discover the relevant phonological properties of their native language, and learn its prosodic, phonetic, and phonotactic characteristics (i.e., Best, McRoberts, & Sithole 1988; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993b; Höhle, Bijeljac-Babic, Herold, Weissenborn & Nazzi, 2009; Friederici & Wessels, 1993; Werker & Tees, 1984; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992; Jusczyk, Luce, & Charles-Luce, 1994). These acquisitions start in the second half of the first year of life. For example, before 6 months, infants are able to discriminate both native and nonnative phoneme contrasts but by 6 months for vowels and 10-12 months for consonants, this discrimination ability is shaped by the native phonological system (Best, et al., 1988; Kuhl, et al., 1992; Werker & Tees, 1984). Similarly, infants' attunement to the prosodic characteristics of the native language is illustrated by the finding that English-learning 9-month-olds prefer listening to words with a trochaic (strong-weak) stress pattern over words with an iambic (weak-strong) stress pattern, the former being more frequent in English (Jusczyk, Cutler, & Redanz, 1993a).

Concerning phonotactic acquisition, different studies have shown that before their first birthday, infants are sensitive to the phonotactic properties of their native language. For example, 9-month-old infants are able to distinguish between legal and illegal sequences in their native language, and show a preference for legal sequences (Jusczyk, et al., 1993b; Friederici & Wessels, 1993; Sebastián-Gallés & Bosch, 2002). Around the same age, infants were also found to be sensitive to the overall frequency of some phonemes or the frequency with which phonotactically legal sequences appear in the words of their language, preferring the more frequent over the less frequent sequences (Jusczyk, et al., 1994; Nazzi, Bertoncini, & Bijeljac-Babic, 2009a; Gonzalez-Gomez & Nazzi, 2012 in press).

In parallel to phonological acquisition, infants become able to map sounds to meaning. Some beginnings of word comprehension have been found as early as 6 months of age, when infants show evidence of comprehending very frequent words like “daddy” and “mommy,” or “hand” and “feet” (Tincoff & Jusczyk, 1999, 2011). By 8 months, infants are able to associate novel words to their referent objects when the object’s movement is coherent with word presentation (Gogate, Walker-Andrews, & Bahrick, 2001). By 12 months, word learning is possible if supported by social cues (i.e. eye gaze, Hollich, et al., 2000) and by 14-16 months, even in the absence of social cues (Schafer & Plunkett, 1998; Werker, Cohen, Lloyd, Casasola, & Stager, 1998), or when using similar-sounding words (Yoshida, et al., 2009; Havy & Nazzi, 2009).

The results cited above clearly demonstrate that infants are able to detect phonotactic patterns in their native language on the one hand, and to map sounds with meanings by their first birthday on the other hand. Nevertheless little is known about whether this phonotactic knowledge learned during the first year of life constrains lexical acquisition.

There is some evidence showing that phonotactic knowledge can affect word learning both in children and adults. Different studies have shown that 3-to-13-year-old children could learn novel words more readily when labels contained frequent sound sequences than when labels contained infrequent sound sequences, a distinction based on phone and biphone positional frequency (Storkel & Rogers, 2000; Storkel, 2001, 2003). Furthermore, phonotactic high-probability pseudo-words have been found to be repeated more accurately (Gathercole, 1995; Edwards, Beckman, & Munson, 2004) and to be better recalled (Gathercole, Frankish, Pickering, & Peaker, 1999) than low-probability pseudo-words in 3- to 8-year-old children. Likewise these effects have also been found in adults, pseudo-words with a frequent phonotactic structure being repeated faster (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997; Vitevitch, Luce, Pisoni, Auer, 1999; Vitevitch, & Luce, 2005), and rated to be more word-like (Frisch, Large, & Prisoni, 2000; Treiman, Kessler, Knewasser Tincoff, & Bowman, 2000; Bailey & Hahn, 2001) than low-probability pseudo-words.

Fewer studies have addressed the question about the existence of phonotactic constraints on early word acquisition. A recent study by Graf Estes, Edwards and Saffran (2011) investigated this issue testing 17-to-20-month-old English-learning infants with two novel object labels being either phonotactically legal (i.e., dref) or illegal in English (i.e., dlef). These infants readily learned the word-object pairings in the phonotactically legal condition, but had difficulties in learning the illegal labels. Additionally, the authors found that the link that exists between phonotactic knowledge and word learning correlated with vocabulary size: the larger the receptive vocabulary, the greater the difference between performance in learning legal and illegal labels. These results show that there are phonotactic constraints on early word acquisition. However, it is not clear what the scope of these constraints is. Given that the legal and the illegal sequences may not be processed in the same way, it is not yet known if these effects are limited to legal versus illegal sound sequences, or if they are also present when containing frequent versus infrequent sound sequences. Hollich et al. (2002) manipulated in the laboratory the phonotactic frequency of a target word (i.e., tirb) by familiarizing 17-month-olds either with a larger number of phonotactically related words (i.e., tirsh, lirb… which occurred twelve times) or with a smaller number (only three times) before conducting a classic word learning task using the preferential looking paradigm. At 17 months of age, infants succeeded in learning a word only if they had been familiarized with twelve phonotactically-related words, showing that familiarity to a phonotactic pattern facilitates word learning. In this study, however, phonotactic probability was manipulated experimentally (by varying the amount of co-occurrences between the phonemes, and using the same phonemes in the target and related words), which could restrict the generalization of the findings.

In the present study, we investigate the role that the phonotactic knowledge about the native language acquired in the first months of life in the infant environment could play when learning new words at the onset of lexical acquisition. Our goal is thus to explore whether (and if so, when) the relative phonotactic probability of a sound sequence in the native language has an impact on infants' word learning. To investigate this question, we exploit the fact that Labial-Coronal (LC) words are more frequent than Coronal-Labial (CL) words in early word production and in the lexicon of many languages.

In early word production studies, it has been found that during the 50-word-stage English-and-French-learning infants tend to produce more Labial-Coronal (LC) words such as “bat” (i.e., words starting with a labial consonant followed by a coronal consonant) than Coronal-Labial (CL) words such as “tab” (i.e., words starting with a coronal consonant followed by a labial consonant). This Labial-Coronal bias has first been interpreted in terms of production constraints according to which producing an LC sequence requires less and easier movements than producing a CL sequence (Ingram, 1974; MacNeilage & Davis, 2000).

However, it has also been shown that in French, the language of the infants tested, LC words are more frequent than CL words (they represent 63% and 37% of all words respectively and 85% and 15% of CVC words respectively, Gonzalez-Gomez & Nazzi, 2012 in press). Although this pattern is very frequent crosslinguistically, it is not universal: a study by MacNeilage and colleagues (1999) presented evidence from 10 languages showing LC biases at the lexical level in all languages except Japanese and Swahili (though see Tsuji, Gonzalez-Gomez, Medina, Nazzi, & Mazuka, in revision, for more nuanced data on Japanese).

Two recent perceptual studies have investigated whether French-learning infants are sensitive to the relative frequency of LC and CL words in their native language. These studies found that infants start preferring to listen to the LC words between 6-7 and 10 months (Nazzi, Bertoncini, & Bijeljac-Babic, 2009a; Gonzalez-Gomez & Nazzi, 2012 in press). These results indicate that by 10 months of age French-learning infants have already learned that LC sequences are more frequent than CL sequences in French. These results are in line with all the data showing that during the first year of life infants become increasingly tuned to the characteristics of their native language (Jusczyk, et al., 1993b; Höhle, et al., 2009; Kuhl, et al., 1994; Werker & Tees, 1984; Jusczyk, et al., 1993a).

The predominance of the LC structures in the lexicon and the early listening preference found for these sequences in French-learning infants makes the LC bias a good candidate to explore how phonotactic probability of a sound sequence in the native language might influence infants' word learning. We predict that LC words will be learned more easily and thus at an earlier age than CL sequences. This prediction is based on the fact that, as suggested by Saffran and Graf Estes (2006), high-probability sequences are composed by very familiar sound combinations, which are phoneme sequences that infants might have experienced many times. This familiarity may decrease the computational load in word learning situations, a hypothesis referred to as "encoding-facilitation" effect. If high-probability sequences are easier to encode and remember, then infants can dedicate more computational resources to mapping sounds with meaning when learning a high-probability new word. On the contrary, when learning low-probability new words, they will need more cognitive resources to encode the sound sequence, which will make linking the sound sequences to their meaning more difficult. In other words, "easily-acquired and early learned words may tend to consist of high-probability words" (Saffran & Graf Estes, 2006, p.35) such as LC words. This is compatible with the results of Graf Estes and colleagues (2011). However, their evidence is limited to an advantage for legal over illegal words, which could be processed qualitatively differently than both high and low probability words.

In a previous study by Nazzi and Bertoncini (2009), no difference between learning LC and CL words was found in 20-month-old French-learning infants. In that study, they used the name-based categorization task (Nazzi, 2005) in which triads of unfamiliar objects are presented. For each triad, two objects are labeled with the same name and the third object is labeled using a different name. In their study, only minimal pairs of words were used (i.e. LC /pid/ and /pit/, or CL /dap/ and /tap/). The authors offered different explanations for this null result. The first one is that phonotactic regularities do have an impact on word learning but that this effect is developmentally transient, and that the infants tested were already too old. The second one is that the task they used was not sensitive enough to show such differences. In order to continue the exploration of such effects, we used in the present experiment a multi-trial cartoon learning task that only presented two objects per trial, with no minimal pairs, to make the task easier. In addition, we used an eye-tracker to record infants' eye movements (similarly to what was done by Graf Estes, et al., 2011) that allows us to analyze the looking behavior instead of the motor behavior of the infants. Additionally, we tested younger infants to explore potential developmental differences.

In Experiment 1, we focus on 16-month-old infants because we know that infants from the age of 14 months on are able to associate two different objects with dissimilar sounding words (i.e., neem and lif; Stager & Werker, 1997; Werker, & Stager, 1998) or even similar sounding words (i.e., bin and din; Yoshida, et al., 2009) in laboratory tasks. Besides, as infants at 16 months display a large amount of variability in their receptive vocabulary (for English-acquiring infants, see Fenson et al., 1994), this allowed to test if vocabulary size is related with learning words of different phonotactic probabilities as has been shown by Graff Estes et al. (2011).

2. Experiment 1

2.1 Materials and Method

2.1.1Participants

Fourteen full-term 16-month-old infants from French-speaking families were tested and included in the analyses (mean age = 16 months 9 days; range: 16 months 1 day – 16 months 23 days; 7 girls, 7 boys). Ten additional infants were tested and excluded from the analyses due to fussiness (N = 3) or because they did not meet the inclusion criteria (N = 7; see paragraph data analysis for details).

2.1.2 Stimuli

Speech Stimuli

The speech stimuli consisted of 8 pairs of monosyllabic C_1VC_2 pseudo-words or low frequency words not likely to be known by infants (see Table 1). Half of them involved labial-coronal (LC) structures and the other half coronal-labial (CL) structures. Items in both conditions were made up of exactly the same consonants and vowels, and all the vowels were completely balanced across conditions. Vowels had been chosen in order to obtain balanced adjacent dependencies between the LC and CL lists for the C_1V, VC_2 and C_1VC_2 sequences of phonemes

(C_1V t(15) = 1.15; p = .33, VC_2 t(15) = 0.48; p = .66, and C_1VC_2 t(15) = 8.11; p = .44) according to the Lexique 3 database (New, Pallier, Ferrand, & Matos, 2001). Therefore, while in Saffran & Graf Estes' (2006) "high probability" sequences were defined in terms of adjacent phonemes, in our experiment all the adjacent frequencies were fully controlled, so that the only difference between the two lists of items used here was the overall relative frequency for the LC and CL non-adjacent sequences in the French lexicon. All items were recorded in a sound-attenuated booth by a female French native speaker. The duration for the LC and the CL pseudowords was similar (386 vs. 375 ms, t(127) = 1.34; p = .22).

Table 1: Pairs of Labial-Coronal and Coronal-Labial CVC sequences used in Experiments 1 and 2.

	Labial-Coronal pairs			**Coronal-Labial pairs**	
	Word/ Pseudo-word1	Word/ Pseudo-word2		Word/ Pseudo-word1	Word/ Pseudo-word2
PairLC 1	bode [bod]	peute [pœt]	PairCL 1	dibe [dib]	teupe [tœp]
PairLC 2	bide [bid]	poute [put]	PairCL 2	daube [dob]	toupe [tup]
PairLC 3	bote [bot]	peude [pœd]	PairCL 3	doupe [dup]	teube [tœb]
PairLC 4	boute [but]	pid [pid]	PairCL 4	dope [dop]	tibe [tib]

Object Stimuli

Images of eight pairs of objects differing in shape, color and texture (Fig. 1) were created for the current study. The reason for using clearly different objects and clearly different words was to facilitate learning of the word-object pairings. All objects were selected so that children and adults would be unfamilar with them. The object pairs were consistently associated with one pair of LC words and one pair of CL words, presented to different infants.

Figure 1. Object stimuli. Pairs of novel objects used in Experiments 1 and 2.

Cartoons

The word-object pairings were embedded into word-learning cartoons, using the Adobe Flash software. The cartoons were constructed to parallel the structure of the films used in Havy, Serres and Nazzi (in revision). In each trial, a female character behind a black board presented the two objects, one at a time (Fig. 2, learning phase). The first object always appeared in the left upper corner of the screen. At the beginning, the object moved horizontally in the left upper part of the display, while it was labeled three times (Look! A [target]! This is a [target]. Look what am I going to do with the [target]!). Then, the object started shifting down, while it was labeled one more time (I put the [target] here). It started moving vertically in the left lower part of the screen and was labeled two more times (Have you seen the [target]? Look carefully at the [target]!) before disappearing. The second object was always introduced in the right upper corner of the display and followed a trajectory analogous to the one of the first object on the right side of the screen. The cartoon experimenter followed with her eyes the objects' movements. Participants were successively trained on each label-object pairing for 30 seconds. The entire learning phase lasted 1 minute and each label was repeated 6 times.

After the learning phase, there was a close up on the face of the cartoon experimenter saying: "Look!" in order to direct infants' fixations to the center of the screen. After the face disappeared, the two objects appeared at the same time, each on the side it appeared during the learning phase, and started moving synchronously in a vertical way, while the out-of-sight speaker said: "Look at the [target]? Where's the [target]!" (Fig. 2, test phase). The test phase was divided into two parts lasting 2500 ms each: a pre-naming phase and a post-naming phase, time-windows that have been shown to cover lexical processes related to word form processing in the second year of life (Mani & Plunkett, 2007; Swingley, Pinto, & Fernald, 1999; Swingley & Aslin, 2000, 2002). The "pre-naming phase" served to evaluate any potential spontaneous preference for a given object, prior labeling. The post-naming phase evaluated the recognition of the target object after its label had been pronounced. This phase started 367 ms after the onset of the target word. This value corresponds to the amount of time required to initiate an eye movement in response to an auditory stimulation in 14-to-24-month-olds and it has been used in numerous studies on early lexical processing (i.e., Mani & Plunkett, 2007; Swingley, et al., 1999; Swingley & Aslin, 2000, 2002).

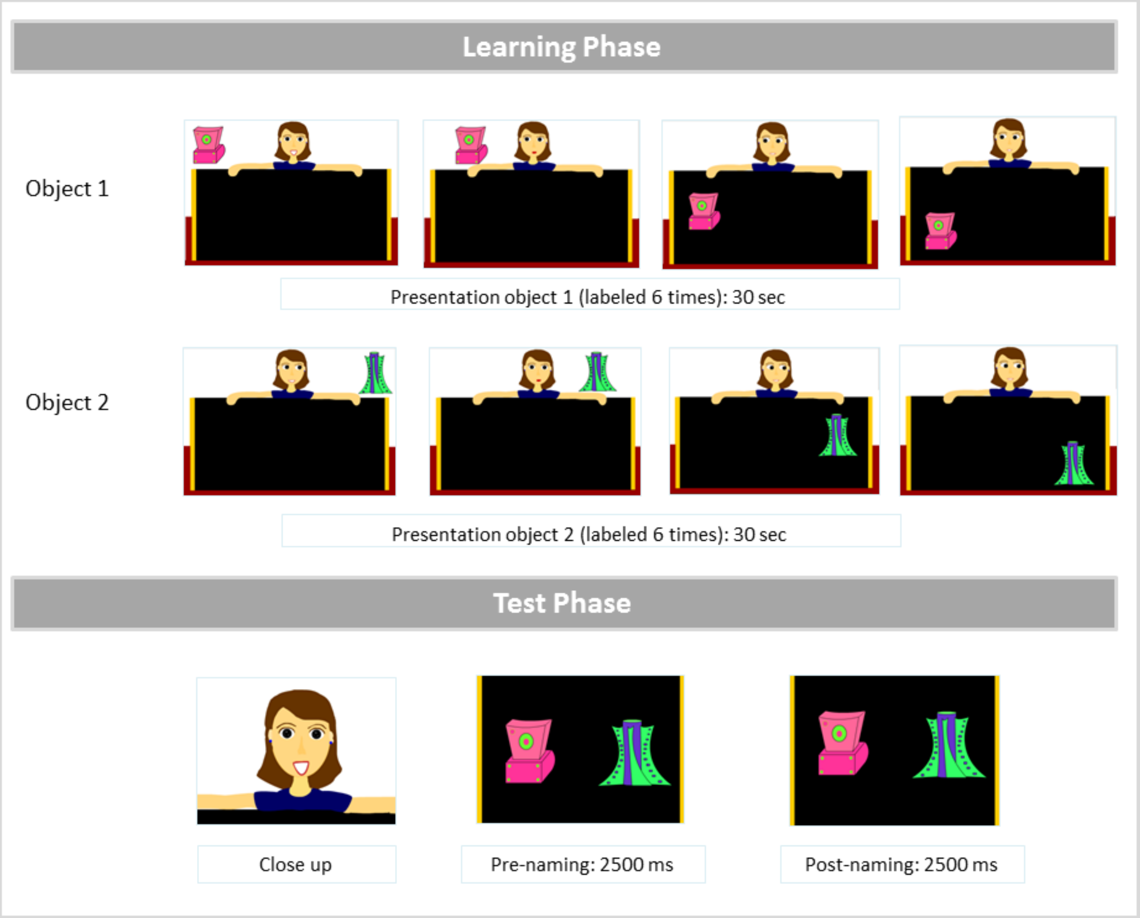

Figure 2. Structure of a word-learning cartoon.

2.1.3 Apparatus and Procedure

The films were presented on a 17'' TFT monitor with an integrated Tobii T60 eyetracking system which was run by a DELL PC computer. A camcorder was mounted above this display to monitor the participants' behavior. The presentation of the stimuli and the storing of the data were performed with the Tobii Studio software.

Participants were tested individually in a dimly lit, sound proof laboratory room. Each infant sat approximately 65 cm from the screen on a caregiver's lap in the center of the test booth. The caregiver was wearing opaque glasses to prevent them from seeing the stimuli and thus minimize the potential for biases. The experimenter controlled the presentation of the stimuli from an adjacent room and monitored the participant's behavior through a video camera. The session began with a 5-point infant calibration. Then a small animation was displayed on the center of the screen before each of the 8 trials until the infant looked at it, in order to start each trial at the center of the screen.

Each trial corresponded to a cartoon, and was thus composed of the learning of 2 LC or CL words (i.e., 'object 1'-'bod', 'object 2'-'pid'), followed by a testing phase evaluating learning/recognition. In the test phase, infants were required to look at one of the two objects (i.e., 'pid'). In each trial one object was the target and the other one was the distractor.

There were eight pseudo-randomized orders counterbalancing for target side, target object, trial order and object label. Thus, between subjects each label was presented and tested on the right and left side and each object was labeled with a LC and with a CL word. The first and the last four trials always contained 2 LC and 2 CL trials. None of the objects or words was presented twice during the test. The experiment lasted approximately 10 minutes.

2.1.4 Data analysis

The eye-tracking data which were used for the analysis consisted of the binocular gaze position at each timestamp, that is, every 16.6 msec. First, the proportion of on-screen looks during the course of the 8 trials was calculated for each infant. We excluded four infants with less than 50% on-screen data (between 41% and 48%) to ensure that infants were sufficiently engaged in the task.

For each trial, we then calculated the proportion of on-screen looks as well as the proportion of time infants spent looking at the target (T) and the distractor (D) in both the pre-naming and the post-naming phases. Therefore, two areas of interest were defined (575 x 895 Pixel), each including one object. Trials in which infants had a strong object bias in the pre-naming phase (> 90% looking to one object) and trials with more than 50% missing data were discarded from the analysis (38/134 trials, 28.4 % of the trials). Finally, only those infants who had at least two analyzable trials per condition were included (N = 3 did not meet this criterion). In the final sample, each participant provided, on average, 6.14 trials out of 8. During each of the 30-sec learning phase, 16-month-old infants spent 10.8 s on average looking at the object and 10.2 s looking at the woman's face.

2.*1.5 Label recognition measure*

To examine object label recognition, the proportion of target looking in the pre-naming and post-naming phases was calculated for each trial by dividing the looking time to the target object by the time spent looking to the distractor and the target (T/(D+T)). For each infant, this measure was then averaged across trials for the two phases (pre-naming/post-naming) and for the two conditions (LC/CL) separately, leading to four values per infant.

2.1.6 Vocabulary measures

To determine the size of the infants' receptive and productive vocabulary, parents were asked to fill out the vocabulary part of the French equivalent (Kern, 2003) of the MacArthur Communicative Development Inventory: Toddlers (CDI; Fenson et al., 1993).

2.2 Results and Discussion

A repeated measures ANOVA with phase (pre- vs. post-naming phase) and condition (LC vs. CL) as within-subject factors and proportion of target looking as dependent variable revealed a significant main effect of phase ($F(1,13) = 8.56$, $p = 0.012$, $\eta^2 = 0.39$) corresponding to an increase in target looking from the pre-naming (M = 48.15%, SD = 12.56%) to the post-naming phase (M = 55.99%, SD = 10.63%). Neither the effect of condition, $F(1,13) = 2.47$, $p = 0.14$, nor the interaction between condition and phase F(1,13) < 1, reached significance. Thus, irrespective of condition, 16-month-olds increased their looking toward the object that was labeled after hearing the name of the target (Fig. 3).

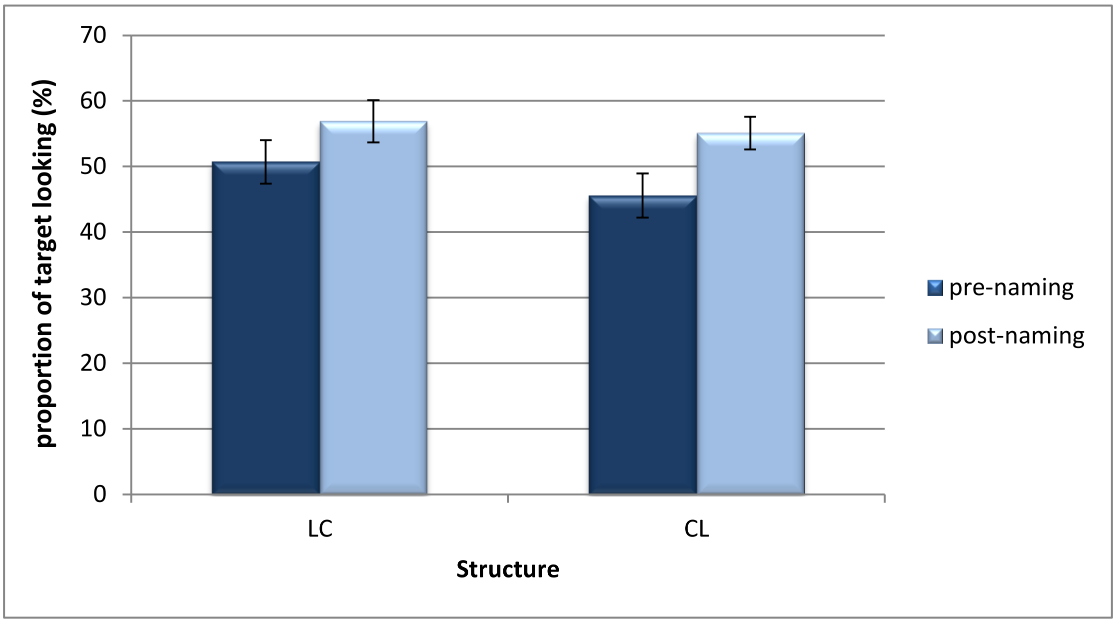

Figure 3. Mean proportion of target looking in % (±1 SE) in the pre-naming and post-naming phases broken down by structures (LC versus CL), at 16 months of age.

2.2.1 Influence of vocabulary size

Graf Estes et al. (2011) reported a positive correlation between target looking and receptive vocabulary size for the phonotactically legal words, and a marginal significant negative correlation for phonotactically illegal words, a pattern which indicates that increasing knowledge about word forms in the native language helps infants to consider a constrained set of sound sequences as possible new words. To evaluate if learning of phonotactically high and low probability sound sequences was modulated by productive and/or receptive vocabulary size, correlational analyses were conducted between target looking and CDI scores. Therefore, the mean difference score of target looking between the pre- and post-naming phases ([% target looking in post-naming phase - % target looking pre-naming phase]) was calculated for each participant and both structures. For both the LC words and the CL words, there was no significant relationship between object label recognition and receptive vocabulary size (LC condition: r = .14; p = .63; CL condition: r = -.90 ; p = .75) and productive vocabulary size, respectively (LC condition: r = -.39; p = .17; CL condition: r = .08 ; p = .79).

The results of Experiment 1 show that 16-month-old infants are able to link both the LC and the CL labels to the unfamiliar object referents presented in the present word learning task. This pattern of result is comparable with that of 20-month-olds who succeeded in learning both LC and CL words in the offline name-based categorization task used by Nazzi and Bertoncini (2009). It could thus be that the relative phonotactic probability of a sound sequence does not impact infants' word learning at all, although phonotactic knowledge about the legality of sequences can constrain infant's word learning by 17/20 months (Graf Estes, et al., 2011). A second possibility however is that 16-month-olds are still too old to manifest such an effect in this task, thus that there is an earlier developmentally transient effect, as Nazzi and Bertoncini (2009) have argued. To explore this possibility a group of younger infants aged 14 months was tested in Experiment 2, using the exact same multi-trial learning task as in Experiment 1.

3. Experiment 2

3.1 Materials and Method

3.1.1 Participants

Twenty-eight[4] full-term 14-month-old infants from French-speaking families were tested and included in the analysis (mean age = 14 months 10 days; range: 14 months 2 days – 14 months 22 days; 10 girls, 18 boys). The data of eleven additional infants were not included in the analyses due to technical problems (n = 1), fussiness (n = 2) or given that they did not fulfill the inclusion criteria (n = 8, see paragraph data analysis for details).

3.1.2 Stimuli, Apparatus and Procedure:

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[4] Analysis of the first fourteen 14-month-olds revealed a marginally significant interaction of phase and condition ($F(1,13) = 4.58$, $p = 0.06$, $\eta^2 = 0.26$). Due to higher variability in 14-month-olds and in order to examine whether this pattern proved to be robust, we doubled the sample size.

The material, apparatus and procedure were the same as in Experiment 1.

3.1.3 Data analysis

The same data analysis and exclusion criteria were used as in Experiment 1. Three infants with less than 50% on-screen data (between 30% and 49%) were excluded from the analysis. 89 trials out of 256 (34.8 %) were discarded because of containing more than 50% missing data and/or because of the infant displaying a strong object preference in the pre-naming phase. Five further infants were excluded because they had less than two analyzable trials per condition after trial exclusion. In the final sample (N = 28), each participant provided 5.96 trials on average. During each of the 30-sec learning phase, 14-month-old infants spent 6.6 s on average looking at the object and 12.6 s looking at the woman's face. Again, the proportion of target looking was calculated as the object label recognition measure and the receptive and productive CDI scores were taken as vocabulary measures.

3.2 Results and Discussion

A repeated measures ANOVA on the proportion of target looking with phase (pre- vs. post-naming phase) and condition (LC vs. CL) as within-subject factors revealed a marginal main effect of condition ($F(1,27) = 3.65$, $p = 0.07$, $\eta2 = 0.16$) corresponding to a tendency for longer target looking in the LC condition (M = 54.22%, SD = 14.26%) compared to the CL condition (M = 49.22%, SD = 15.09%). There was no significant effect of phase ($F(1,27) < 1$) but a significant interaction between phase and condition ($F(1,27) = 7.73$, $p = .01$, $\eta2 = .22$). Comparisons within each structure revealed that while the proportion of target looking increased significantly across phases for the LC words (pre-naming: M = 50.35%, SD = 10.90%; post-naming: M = 58.09%, SD = 16.26%; $t(27) = 2.50$, $p = .02$, Cohen's d = .47), no effect of phase was found in the CL condition (pre-naming: M = 51.42%, SD = 13.34%; post-naming: M = 47.01%, SD = 16.61%; $t(27) = 1.33$, $p = .19$, see Fig. 4).

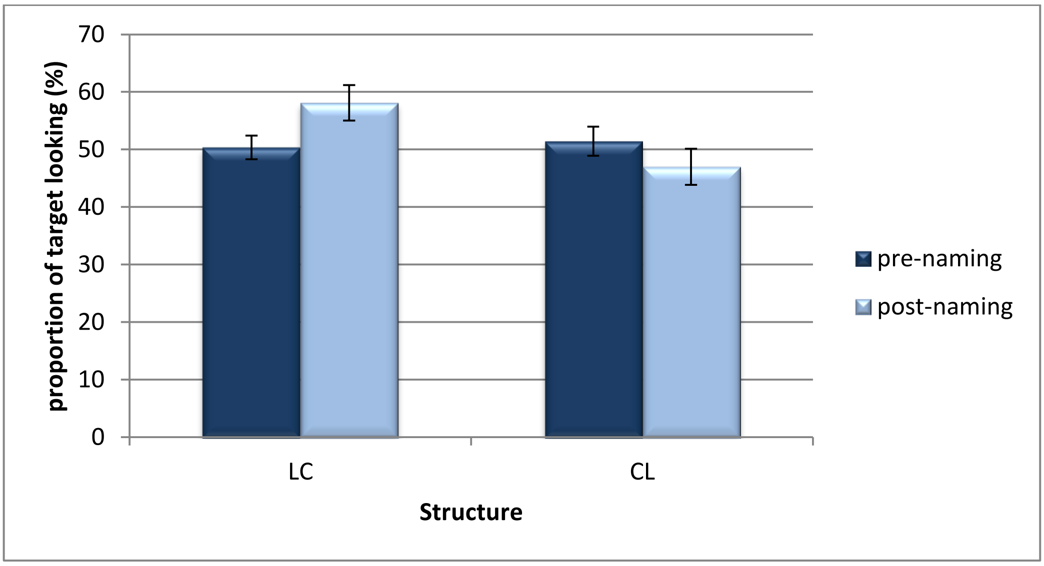

Figure 4. Mean proportion of target looking in % (±1 SE) in the pre-naming and post-naming phase broken down by structure (LC versus CL), at 14 months of age.

The results of Experiment 2 show that 14-month-old infants were able to link the most frequent phonotactic LC structures but not the less frequent CL words to the unfamiliar object referents presented in the word-learning task. These results are the first piece of evidence showing that infants' word learning is impacted not only by knowledge about the phonotactic legality of sound patterns (Graf Estes et al., 2011) but also by the relative phonotactic probability of a sound sequence. Furthermore these results suggest that phonotactic effects impact learning differently during development, since the 16-month-olds tested in Experiment 1 and the 20-month-olds tested in Nazzi and Bertoncini (2009) did not present such an effect.

3.2.1 Correlation with vocabulary size

As in Experiment 1, the mean difference score of target looking between the pre- and post-naming phases ([% target looking in post-naming phase - % target looking pre-naming phase]) was calculated for each participant and for both structures in order to examine the relationship with infants' vocabulary size. For both the LC words and the CL words, there was no significant relationship between object label recognition and productive vocabulary size (LC condition: $r = .24$; $p = .20$; CL condition: $r = -.02$; $p = .91$). However, there was a trend towards a positive correlation between receptive vocabulary size and CL word recognition (r = .32; p = .09), that is there was a tendency for a link between the number of understood words in the CDI and the likelihood of learning CL words. This trend in the data was not observed for LC words (r = .01, p = .97).

4. General Discussion

The goal of the present study was to explore whether the relative phonotactic probability of a sound sequence in the native language has an impact on infants' word learning. Accordingly, we tested 14- and 16-month-old French-learning infants using a multi-trial learning task involving eight pairs of pseudo-words consisting of phonotactically legal CVC strings paired with unfamiliar object referents. Half of the pseudo-words were Labial-Coronal sequences and the other half were Coronal-Labial sequences. These patterns vary in their relative frequency, LC sequences being much more frequent in the French lexicon than CL ones (Gonzalez-Gomez & Nazzi, 2012). The results of Experiment 1 show that 16-month-old infants were able to associate LC as well as CL labels to the unfamiliar object referents, with no difference in performance for the two types of labels. However, in Experiment 2, 14-month-old infants were only able to link the LC labels to the unfamiliar object referents, showing that infants' knowledge of their native language phonotactic patterns influences their word learning. Taken together, both experiments show that more frequent phonotactic word patterns were easier to learn, and were thus learned at an earlier age than infrequent phonotactic words. Therefore, the present findings are the first piece of evidence showing that prior native language phonotactic knowledge constrains word learning so early in development, that is, at 14 months, extending to novice word learners previous results on more expert 18-month-old infants (Graf Estes, et al., 2011), children (Gathercole, 1995; Gathercole, et al., 1999; Storkel & Rogers, 2000; Storkel, 2001; 2003; Edwards, et al., 2004) and even adults (Vitevitch, et al., 1997; Vitevitch, et al., 1999; Vitevitch, & Luce, 2005; Frisch, et al., 2000; Treiman, et al., 2000; Bailey & Hahn, 2001).

Besides age, the present study also differs in two other ways from the ones having found later phonotactic effects, which relates to the kind of phonotactic knowledge that is explored. Our study exploits the presence of an LC bias in the

French lexicon (the higher frequency of LC words over CL words) to explore effects of relative frequency rather than legality on the one hand, and of non-adjacent rather than adjacent phonotactic dependencies on the other hand. Regarding the first point, the only other study showing phonotactic effects in infancy is the one by Graf Estes et al. (2011) establishing that English-learning 17-20-month-old infants can learn new label-object associations only if the labels are phonotactically legal in their native language. While the findings of both studies are in line, the present study extends the scope of the phonotactic effect from differences in legality to differences in relative frequency. This distinction is crucial. In the legality case, illegal sequences are sequences of sounds that are never heard as word-like units in the input, and that cannot be a word of the native language. So as infants become more proficient word learners, they should be less and less prone to learning words with phonotactically illegal structures. Although Graf Estes et al. (2011) only tested one age group, correlation analyses showing that the size of the phonotactic effect increased with receptive vocabulary suggests that infants become more reluctant to learn words with illegal phonotactics. In the present case manipulating relative frequency, both high- and low-probability sequences occur as word-like units in the input, and both LC and CL stimuli were possible words in French. Therefore, infants need to be able to learn both types of words. Accordingly, the phonotactic effect we found corresponds to the fact that infants initially have difficulties learning the low-frequency words but become better learners of the low frequency words as they get older (from 14 to 16 months) and/or as their vocabulary increses (trend for a correlation between receptive vocabulary and CL word learning at 14 months). Hence, while the phonotactic effect becomes larger when comparing the acquisition of legal versus illegal sequences (Graf Estes, et al., 2011), it becomes smaller when comparing the acquisition of high versus low frequency patterns.

This pattern of a developmental reduction of the relative frequency phonotactic effect is congruent with previous results (Nazzi & Bertoncini, 2009) that had failed to show such an LC/CL phonotactic effect in 20-month-old infants, who appeared to learn equally well LC and CL words. To explain this lack of effect, the authors had proposed that the task might not have been sensitive enough (infants had to provide a motor response to choose the target object), or infants were already too old. The present study suggests that task itself may not solely explain the lack of effect at 20 months, since no effect was found here at 16 months using a different task. However, only a direct comparison of the outcome of both tasks at the same age could confirm this possibility. On the other hand, our study shows that age must have contributed to the lack of results in Nazzi and Bertoncini (2009), since the phonotactic effect that was clearly present at 14 months could not be found at 16 months. Taken together, both studies suggest that this relative frequency phonotactic effect decreases, or becomes more subtle, as infants become better word learners.

The second important difference between the present study and previous ones on phonotactic effects is due to the kind of phonotactics manipulated. Previous studies focused on adjacent properties of the specific items used as stimuli, in particular, on the frequency of clusters or adjacent diphones (i.e., Edwards, et al., 2004; Frisch, et al., 2000; Vitevitch & Luce 1998). On the contrary, the present study focused on the relative frequency of two structures differing in non-adjacent properties: the learning advantage was found for a structure (Labial-vowel-Coronal) that is more frequent in the target language than the other structure (Coronal-vowel-Labial), and the advantage is due to an asymmetry in the order of occurrence of the two non-adjacent consonants that are separated by a vowel. Therefore, the present study extends the scope of phonotactic effects on word learning from adjacent to non-adjacent dependencies, showing that the acquisition of both adjacent (Jusczyk, et al., 1993b; Jusczyk, et al., 1994; Mattys, et al., 1999; Mattys & Jusczyk, 2001) and non-adjacent (Gonzalez-Gomez & Nazzi, 2012; Nazzi, et al., 2009) phonotactic dependencies by 9/10 months of age both impact later lexical acquisition.

Importantly though, it further appears that the present non-adjacent effect is not driven by knowledge regarding the relative frequency of the specific items used, since the stimuli were chosen so that the frequencies of all adjacent diphones and of the CVC items themselves were matched across the LC and LC structures (see Gonzalez-Gomez & Nazzi, 2012, for similar effects in early perception). Hence the effect in Experiment 2 is likely to reflect the fact that 14-month-old infants are processing differently two abstract phonotactic structures/categories. If this is the case, then it predicts that the same word learning advantage for LC items should be found when presenting infants with specific LC and CL items chosen so that the LC items would have lower diphone and triphone frequencies than the CL items, a predictions that will have to be evaluated in future research.

Lastly, the present findings bring clear evidence showing that the effect of phonotactic knowledge on word learning changes developmentally. At 14 months of age, infants were only able to associate the high-probability labels (LC) with the referent objects, while 16-month-olds were able to associate both frequent and infrequent phonotactic labels. These developmental changes can be explained by different hypotheses. The first possibility would be that phonotactic properties impact word learning, but only at the very beginning of this process; as vocabulary increases, the impact of phonotactics on word learning disappears. This possibility is not very plausible given that the evidence reviewed earlier of phonotactic effects on word learning in older infants (18-month-olds, Graf Estes, et al., 2011), children (Gathercole, 1995; Gathercole, et al., 1999; Storkel & Rogers, 2000; Storkel, 2001; 2003; Edwards, et al., 2004), and even adults (Vitevitch, et al., 1997; Vitevitch, et al., 1999; Vitevitch & Luce, 2005; Frisch, et al., 2000; Treiman, et al., 2000; Bailey & Hahn, 2001). However, as discussed above, since different types of phonotactic regularities were explored in the present study (non-adjacent versus adjacent), it remains possible that they would follow different developmental trajectories, which would need to be directly assessed by studies exploring the two types of regularities at the same ages and using the same tasks.

A second possibility is that the developmental changes are due to "encoding facilitation," as suggested by Saffran and Graf Estes (2006), according to which words with a frequent phonotactic structure are easier to encode phonologically, and thus benefit from more available cognitive resources to be linked to referents. As vocabulary size increases, encoding proficiency improves, leading to a reduced phonotactic effect. This possibility is in line with our findings of better performance for the less frequent CL items at 16 compared to 14 months, and with the trend towards a positive correlation between receptive vocabulary size and CL word learning at 14 months. However, this hypothesis needs to be modulated by the fact that phonotactic effects were found even in expert word learners such as adults (Vitevitch, et al., 1997; Vitevitch, et al., 1999; Vitevitch & Luce, 2005; Frisch, et al., 2000; Treiman, et al., 2000; Bailey & Hahn, 2001). Therefore, it is likely that phonotactic effects could be found at all ages under conditions requesting high cognitive load. Regarding the 16-month-olds tested in Experiment 2, we predict that presenting fewer repetitions of each label, teaching more words at the same time, or using minimal contrasts (such as LC pat/bat or CL tub/dub, as done in Nazzi & Bertoncini, 2009) might reveal phonotactic effects at 16-months. This possibility is in line with results obtained for children using tasks that required high cognitive load such as memory tasks requiring the recall of a list of words (Gathercole, et al., 1999), word-learning tasks presenting fewer repetitions of each label (Storkel, et al., 2001), or repetition tasks presenting words with more syllables (from two to five syllables, Gathercole, 1995).

At this point, we would like to discuss a couple of issues raised by the findings of the present study that could be explored in the future. The first issue relates to the kind of phonotactic patterns that can impact word learning. Given the proposal and emerging data regarding the different roles that consonants and vowels play at different linguistic processing levels (Nespor, Peña, & Mehler, 2003; Havy & Nazzi, 2009; Nazzi, 2005; Nazzi, Floccia, Moquet, & Butler, 2009b), it would be of interest to compare the impact of consonantal and vocalic phonotactic regularities on word learning. Second, based on the “encoding facilitation” hypothesis, the fact that LC word forms are easier to encode than CL word forms might facilitate not only their mapping to objects in word learning tasks, but might also facilitate their processing at other lexical or prelexical levels. One level at which such an effect could be found is on the ability to segment word forms from fluent speech. Such a facilitative segmentation effect has been found for other phonotactic regularities in infants (Mattys, Jusczyk, Luce, & Morgan, 1999; Mattys & Jusczyk, 2001) and adults (Mersad & Nazzi, 2011; Finn & Hudson Kam, 2008; Mattys, White, & Melhorn, 2005). This possibility is currently under investigation, and results so far show that LC sequences are also easier to segment than CL sequences at 10, but not 13 months of age (Gonzalez-Gomez & Nazzi, in preparation).

In conclusion, the present study provides new evidence showing that words with a frequent phonotactic structure are acquired at an earlier age than those with a lower probability. More importantly, these findings show that prior knowledge about phonotactic regularities in the native language has an effect on word learning, supporting theories according to which lexical acquisition is influenced by prior or parallel phonological acquisition. Furthermore these results show the existence of developmental changes between 14 and 16 months of age, suggesting that effects of relative phonotactic frequency on word learning might only be observed in situations in which computational load is high.

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What relationship, if any, exists between prior phonological knowledge and word learning?

The results of this section show:

- 14-month-old French-learning infants are able to learn novel LC words but not novel CL words.
- At 16 months of age French-learning infants are able to learn both LC and CL pseudo-words.
- These data suggest the existence of developmental changes taking place between 14 and 16 months of age.
- Words with frequent phonotactic structures are learned at an earlier age than infrequent phonotactic words.
- The effect of phonotactic structure was found to be temporary in the present kind of study.

➔ According to the results presented in this section, prior knowledge of phonotactic patterns of the native language can later influence infants’ word learning.

General Discussion

> *“Language is the road map of a culture.*
> *It tells you where its people come from*
> *and where they are going.”*
> *Rita Mae Brown*

The present dissertation work has been dedicated to the exploration of the processes by which infants acquire the set of permissible sound combinations and the frequency at which these combinations occur in their native language, named phonotactic properties. Infants, young children and adults have all been shown to be able to detect, analyze, store and use phonotactic regularities (infants: Friederici & Wessels, 1993; Mattys & Jusczyk, 2001a; Mattys, et al., 1999; Jusczyk, et al., 1993b; 1994; Sebastián-Gallés & Bosch, 2002; children: Storkel & Rogers, 2000; Storkel, 2001; 2003; 2004b; Gathercole, et al., 1999; Gathercole, 1995; Edwards, et al., 2004; adults: Vitevitch, et al., 1997; Vitevitchet al., 1999; Vitevitch & Luce, 2005; Frisch, et al., 2000; Treiman, et al., 2000; Bailey & Hahn, 2001). Learning phonotactic properties allow listeners to build a repertoire of the permissible sound sequences in a given language and to store information about the frequency of occurrence of these sound sequences. This phonotactic knowledge facilitates on one side the detection of exemplars that belong to the same linguistic system, being particularly relevant for infants growing up in bilingual environments (Sebastián-Gallés & Bosch, 2002; Jusczyk, et al., 1993). On the other side, it enables the identification of possible word-like units. Both tasks are especially important during language acquisition.

Reviewing the questions addressed and the answers found

In this work various unanswered questions about the acquisition of phonotactic properties have been addressed. First, we asked whether or not infants can detect and learn non-adjacent phonotactic dependencies. This is a very important question since languages embed regularities between adjacent elements and also between non-adjacent or distant elements. To explore this question, we exploited the fact that in French, sequences starting with a Labial consonant followed by a Coronal consonant (i.e. “bat”) are much more frequent than the opposite pattern (“tab”). This is a non-adjacent dependency, since both consonants are separated by a vowel. Using the head-turn preference procedure (HPP), French-learning infants’ preference for either LC or CL sequences was tested at 7 and 10 months of age. To ensure that infants were reacting to the relative position of non-adjacent consonants, all adjacent frequencies were fully controlled. Our results showed that 10- but not 7-month-olds prefer to listen to LC sequences compared to the opposite CL pattern. We interpreted this result as reflecting infants' acquisition of the phonotactic properties of French, namely here the LC bias. Control experiments were nevertheless conducted to explore a possible preference for L-initial or C-final sequences that could eventually explain the LC preference found at 10 months. Importantly, these experiments failed to show any preference for L-initial or C-final sequences at 10 months of age. This confirmed that 10-month-olds' preference for LC sequences was not due to positional frequencies (L-initial and C-final), but to the relative position of the non-adjacent consonants (LC). Furthermore, the results of the control experiments showed that 7-month-old infants have a preference for C-initial and C-final sequences, which are both more frequent in French. Taken together, these results suggest that between 7 and 10 months a change from sensitivity to local properties to non-adjacent dependencies takes place.

Once we established that 10-month-old infants are sensitive to non-adjacent phonological dependencies, different questions arose concerning the level at which such kind of acquisitions are made. The characteristics of the French lexicon offered a great opportunity to explore this question. A more detailed analysis of the lexicon revealed that even if, overall, LC sequences are more frequent than CL sequences, this bias is not homogenous. There were some pairs of phonemes presenting either no LC bias or even a CL advantage. More interestingly, we found that these asymmetries were present at the level of classes of consonants defined by their manner of articulation. Indeed, the LC advantage was found for plosive and nasal sequences but not for fricative sequences. These differences at the level of pairs of phonemes, and classes of consonants allowed us to study the level at which the LC bias is acquired. Three different possibilities were considered. The first possibility is that these non-adjacent regularities are learned at a global level, meaning that infants learn that generally LC sequences are more frequent than CL ones. The second possibility is that infants acquire these dependencies at the phonetic category level, meaning that the bias varies according to the consonant classes defined by manner of articulation (LC for plosives and nasals, and CL for fricatives). The third possibility is that this bias is learned at an item-based level, that is, for each pair of consonants separately. Accordingly, we explored whether 10-month-old French-learning infants' preference for LC words is sensitive to differences in the size and direction of the LC bias across consonant classes and phoneme pairs. Three experiments were conducted to explore this issue, one for each class of consonants (plosives, fricatives and nasals). For plosive and fricative sequences, three different sub-experiments were conducted: the first one presenting a mix of consonants of the same manner (plosive or fricative), the second one using a pair with an LC bias, and the third one using a pair with a CL bias. Given that French only has one pair of L/C nasal consonants, only that pair was used (which has an LC bias). The results showed the existence of an LC bias for plosive and nasal sequences, but a CL bias for fricative sequences. This pattern of results suggests that the non-adjacent phonotactic acquisition regarding the relative sequential position of L and C consonants in words is acquired at the level of classes of consonants defined by their manner of articulation (rather than acquired either for every individual pair separately or for all consonants taken together). These findings bring further support to the notion that this bias emerges as a consequence of the acquisition of native language properties.

In addition, questions about the mechanisms underlying non-adjacent phonological acquisitions were also addressed. First, we explored the role that maturation has on such acquisitions. To do so, we tested a population in which maturational level and time of exposure to the linguistic input can be distinguished, that is preterm infants. The results of this study provided information about the origin of the LC bias, the role of maturation and input exposure on early speech perception, and the development of language in infants born prematurely. Indeed, sensitivity to the non-adjacent LC phonological dependency was tested in a group of 10-month-old French-learning infants born prematurely (between 26 and 33 weeks GA) and in two groups of full-term controls, the first one matched on time of exposure to linguistic input, that is on chronological age (±10 months), and the second one matched on maturational age (±7 months). The results showed that by 10 months of chronological age preterm infants are also sensitive to this non-adjacent phonological dependency, preferring LC over CL sequences. Furthermore, the preterm 10-month-old pattern resembles that of the full-term 10-month-olds (same listening age) more than that of the full-term 7-month-olds (same maturational age). Concerning the origins of the LC bias, these results suggest that the LC bias is not solely triggered by maturational constraints. Rather, it appears that the emergence of the LC preference is a result of the exposure to the linguistic input, as we had initially proposed. Lastly, these results bring the first piece of evidence suggesting that preterm infants' developmental timing for phonotactic acquisition is based on input experience and not on maturational age as it has been shown for prosodic acquisition. Thus, language acquisition in preterm infants does not appear to be delayed overall: some linguistic properties are acquired within the same period as found for full-term infants. Together, our results suggest that neural immaturity affects different language levels in different ways.

To continue exploring the origins of the LC bias, the role of the linguistic input was explored in more detail. It is important to remember that the LC bias was first found in early production studies and that the first interpretation of the LC bias was articulatory, authors claiming that LC sequences are easier to produce than CL sequences (MacNeilage & Davis, 2000; but see Rochet-Capellan & Schwartz, 2005a; 2005b). Therefore, a good way of testing whether the LC bias is due to articulatory constraints rather than to perceptual ones, is to test a population exposed to a linguistic input with no LC bias. In this case, while the articulatory hypothesis predicts similar effects, the perceptual hypothesis predicts a behavioral pattern in line with the characteristics of the linguistic input. A corpus analysis of English, Estonian, French, German, Hebrew, Japanese, Maori, Quichua, Spanish and Swahili (MacNeilage, et al., 1999) had revealed that all languages but Japanese and Swahili have an LC bias. Accordingly, in collaboration with Reiko Mazuka from the RIKEN institute, we first conducted an analysis of the Japanese lexicon both in an adult corpus and in an infant-mother conversation corpus. The goal was to verify that the Japanese lexicon does not show an LC bias since the corpus used by MacNeilage and Davis (2000) was very small (68 words extracted from a travel dictionary). The analysis revealed the lack of a clear LC or CL bias in Japanese. Based on this, the emergence of an LC bias was tested in 7- and 10-month-old Japanese-learning infants. The results failed to show any preference for either LC or the CL sequences at both ages. This null result is in line with our analyses of the Japanese lexicon showing no LC or CL bias. Furthermore, 7- and 10-month-old French-learning infants were tested using the Japanese stimuli. The results showed that 10- but not 7-month-olds prefer the LC sequences that are more frequent in their native language. Taken together, these results confirm that the LC preference is a result of exposure to the linguistic input.

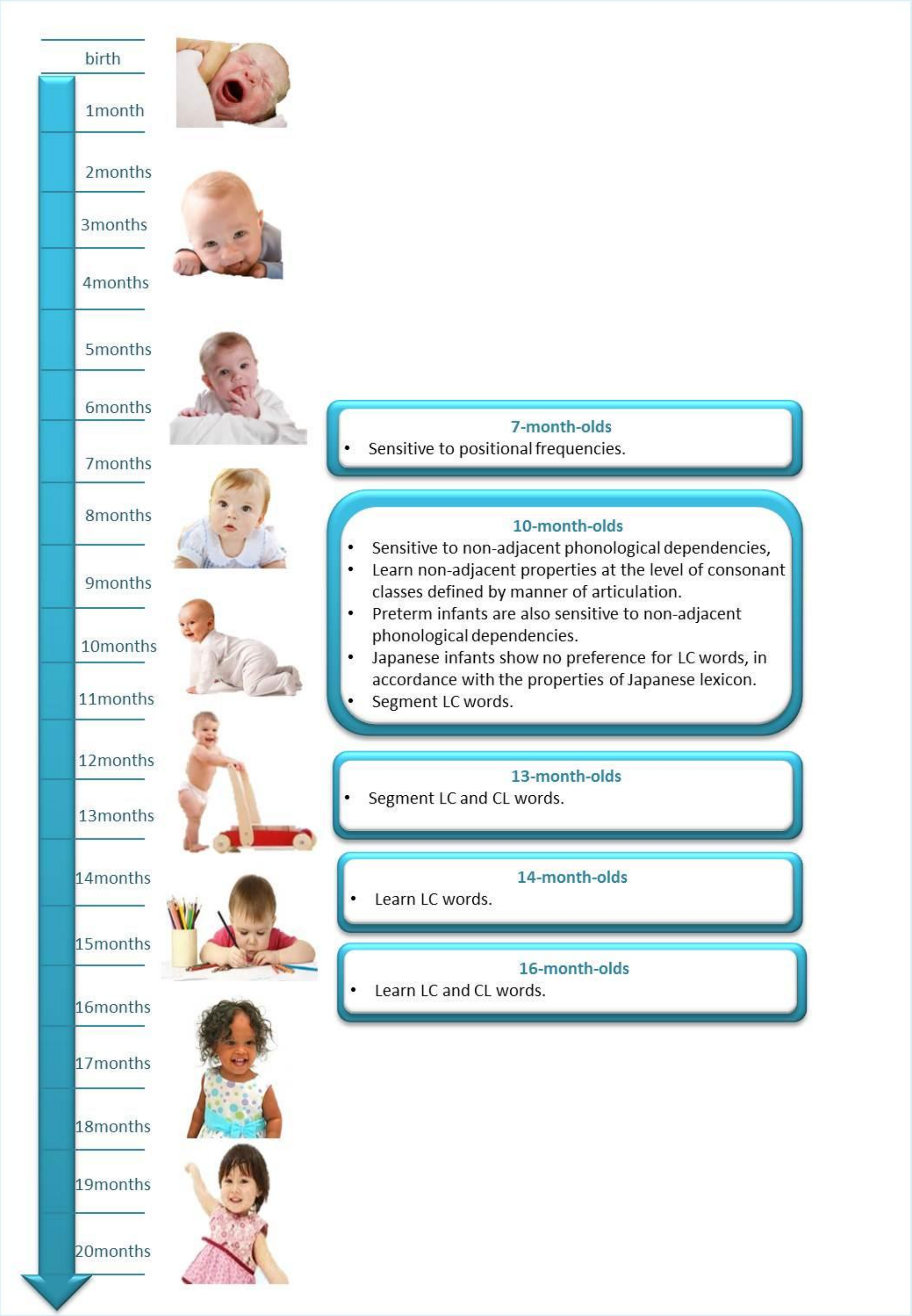
Lastly, this dissertation work was also interested in the link existing between early speech perception and early lexical acquisition. In the past, a considerable number of studies have been dedicated to explore how infant speech perception abilities become attuned to their native language on one side, and how infants are able to extract word-like units and how they start associating these word-like units with meaning representations on the other side. Nevertheless, there are very few studies focusing on how these processes interact.

Consequently, we first explored whether or not prior phonotactic knowledge constrains word segmentation. To do so, infants' ability to segment LC and CL sequences inserted within passages was tested, knowing that 10-month-old French-learning infants are already sensitive to these non-adjacent phonological dependencies, and that they show a preference for LC sequences. The results showed that 10- as well as 13-month-old infants recognize LC sequences presented in the passages during familiarization, while they were not able to recognize the CL sequences. To further explore infants' failure to extract CL words, a second experiment was run. In this new experiment, only passages containing CL words were presented, to avoid a possible competition effect triggered by the typicality of LC sequences. The results of this experiment showed that 13- but not 10-month-olds were able to recognize the CL sequences presented during familiarization. This suggests on one side, that 10-month-olds are not able to segment CL sequences. On the other side, it suggests that the failure of the 13-month-old group in the first experiment was possibly due to the existence of a competition effect. Taken together, these findings suggest that prior phonotactic knowledge has an impact on later word segmentation, frequent phonotactic sequences being easier to segment (as shown by the fact that they are segmented at an earlier age) than infrequent ones.

Second, we investigated the link existing between prior phonotactic knowledge and word learning. For this, we tested the ability of 14- and 16-month-old infants to learn new LC or CL labels during a word-learning task. The results showed that 14-month-old infants are able to learn the LC labels, while there was no evidence that they could learn the CL labels. However, 16-month-old infants were able to learn both

LC and CL labels. These results show that prior phonotactic knowledge influences early word learning, words with a frequent phonotactic structure being easier to learn (they were learned earlier in life) than words with an infrequent phonotactic structure.

To conclude this part, we present a figure summarizing the results presented in this section.



7-month-olds
- Sensitive to positional frequencies.

10-month-olds
- Sensitive to non-adjacent phonological dependencies,
- Learn non-adjacent properties at the level of consonant classes defined by manner of articulation.
- Preterm infants are also sensitive to non-adjacent phonological dependencies.
- Japanese infants show no preference for LC words, in accordance with the properties of Japanese lexicon.
- Segment LC words.

13-month-olds
- Segment LC and CL words.

14-month-olds
- Learn LC words.

16-month-olds
- Learn LC and CL words.

Figure 3. Summary of the main results obtained in the dissertation.

Putting the pieces of the puzzle together

In the present dissertation, we explored infants' acquisition of non-adjacent phonological dependencies. As mentioned before, this intellectual journey started investigating early speech perception and led us to early lexical acquisition. During this entire journey, the same phonotactic dependency was tested at different levels. To the best of our knowledge, there are no other studies testing the same phonological contrast at all these different levels. This provides us with an exceptional opportunity to observe a more complete picture of the acquisition of a phonotactic contrast. In this section we will try to put together the pieces of this puzzle.

To begin, we will briefly review two different models that propose a link between speech perception and word learning. The first one is the Word Recognition and Phonetic Structure Acquisition (WRAPSA) model by Jusczyk (1993, 1997). According to this model, infants start analyzing the acoustic signal using general auditory analyzers. These auditory analyzers extract the spectral and temporal information of the signal. At this stage, speech processing is not language specific and it is neutral to the language of the environment. After some months of exposure, the sounds of the native language become familiar, and the output of the auditory analyzers starts to be weighted, giving prominence to the most important features for processing contrasts between words. Then, based on the weighted output, infants start to extract recurrent patterns allowing the identification of word-like units. Finally, once infants have extracted the representation of a word-like unit, they will try to match it with preexisting known words of the mental lexicon. If a close match is found then the word is recognized and the word meaning, if known, is activated. However, if no close match is found, the input might be reprocessed to find a suitable match, and in case of failure, the new representation will be store with or without its referent meaning.

The second one is the Processing Rich Information from Multidimensional Interactive Representations (PRIMIR) model proposed by Werker and Curtin (2005). According to this model, infants are born with a set of biases that act as filters and interact with infants' developmental level and the specific language-learning task demanded. All these filters, coupled with general learning mechanisms, are able to compute statistical analyses, guaranteeing the acquisition of only linguistically possible combinations. In this perspective, all the information is organized and grouped in three multidimensional planes. The first one is the general perceptual plane. This plane processes and organizes all the phonetic and indexical properties of the signal, forming and storing exemplar-like distributions of the input and its frequency of occurrence. All the information is context-sensitive and is grouped by co-occurrence, feature similarity or by any other statistical regularity. The second plane is the word form. Based on the exemplar-distributions, sequences forming cohesive units are extracted, stored and linked to concepts in this plane, creating meaningful words. Once a sufficient number of meaningful words are accumulated, a generalization of commonalities takes place and high order regularities emerge, forming a system of contrastive phonemes, that are stored and processed in the Phoneme plane. All these planes interact between themselves and, depending on the demands of the task and the developmental level of the listener, one or other level of information can be attended.

Keeping in mind both models, we propose a framework explaining phonotactic acquisition as evidenced in our experimental work:

- Level 1: From birth infants start processing and analyzing the acoustic signal to extract its spectral and temporal information by means of "general acoustic analyzers" (Jusczyk, 1993, 1997). At this point, speech processing is not language specific, and phonotactic properties of the language have not yet been learned.
- Level 2: After some months of exposure to the linguistic input, infants have accumulated a great amount of information about their native language, allowing them to specify the sounds of their language. At this stage, speech processing starts being language specific and infants become attuned to the sounds of their native language. Frequent phonetic categories are specified earlier than less frequent ones (Anderson, Morgan, & White, 2003).
- Level 3: Once infants have acquired the sounds of their native language, the input is analyzed to find high order phonotactic regularities allowing the identification of possible word-like units. The frequency of occurrence of such regularities is tracked. In addition all the regularities found are stored

and grouped with other regularities having common properties, such as feature similarities (Werker & Curtin, 2005).

- Level 4: Based on these regularities infants form word-like representations, which are identified and extracted from the speech stream. “Each time that a word is processed there is a reduction in the processing time that marks this practice increment…” (Ellis, 2002, p.152). Thus, the time of processing of a word-like representation depends on its frequency of occurrence, more frequent structures being identified more easily and more quickly than less frequent structures. At this level, infants have a “protolexicon” containing sound sequences that co-occur frequently (Ngon, Martin, Dupoux, Cabrol, & Peperkamp, in revision).
- Level 5: Infants start matching word-like representations with their associated referents and store them in the mental lexicon. Words with a frequent phonotactic structure are easier to encode phonologically, and thus benefit from more available cognitive resources to be linked to referents (Saffran & Graf Estes, 2006).
- Level 6: As vocabulary and developmental level increases, exposure to less frequent structures increases as well, and encoding proficiency improves, reducing the phonotactic effects, which eventually vanish. However under conditions requesting high cognitive load these effects can reemerge.

It is important to highlight that in this framework, development does not correspond to a linear and homogeneous trajectory through the different levels, in the sense that at any time, infants can have access to different levels (according for example to the task they are facing), and that not all phonotactic properties are acquired at the same time (depending, for example, on its kind, or its frequency in the input).

After describing this framework, we will now place the results obtained in the present dissertation into this theoretical structure. Given that the younger infants tested in this dissertation were 7-month-olds, we will start at level 2 of the framework.

Level 2: Becoming attuned to the sounds of the language

At this level, infants become attuned to the sounds of French. In support of the proposal that frequent phonetic categories are acquired earlier, we found that French-learning 7-month-olds have a preference for coronal consonants (experimental part 1.1), which is the most frequent consonantal category in terms of place of articulation. This coronal preference suggests that at 7 months, French-learning infants have learned something about the relative frequency of coronal and labial consonants in their native language.

Level 3: Finding high order phonotactic regularities

At this level, having specified the sounds of their native language, infants analyze the input to find high order phonotactic regularities allowing the identification of possible word-like units.

Accordingly, given the properties of the Japanese lexicon, in which LC sequences are not high order regularities in Japanese, we found that Japanese-learning infants do not develop a clear sensitivity for these phonotactic properties (experimental part 1.4). In contrast, both preterm (experimental part 1.3) and full-term (experimental part 1.1) French-learning infants with 10 months of exposure to the input have learned that LC sequences are more frequent in French than CL sequences, and they appear to consider them good word-like candidates. This is shown by the emergence of a clear preference for these structures. Moreover, the LC representations seem to be stored and organized by feature similarities, in this case consonant classes defined by manner of articulation, for which infants keep track of frequency of occurrence. This explains why infants show an LC preference for plosive and nasal sequences, but a CL preference for fricative sequences (experimental part 1.2).

Level 4: Forming word-like representations

At this level, based on these high order regularities, it is proposed that infants start forming word-like representations. Given our previous findings, we had hypothesized that French-learning infants would be able to extract LC word-like representations more easily and more quickly than CL word-like representations. Our findings showing that 10-month-old infants can segment LC but not CL sequences (experimental part 2.1) support these predictions.

Level 5: Matching word-like representations with referents

At this level, having formed word-like representations, infants start associating these sound units with their meaningful referents. Words with frequent phonotactic structures should be easier to encode phonologically, and thus easier to learn, than less frequent ones. This is supported by our finding that 14-month-old infants are able to learn LC but not CL sequences (experimental part 2.2).

Level 6: Improving encoding proficiency

As vocabulary and developmental level increases, infants' exposure to less frequent structures increases and encoding proficiency improves. Consequently, the effects of phonotactic knowledge on lexical acquisition should diminish. Accordingly, we found that infants are able to segment sequences with a less frequent phonotactic structure by 13 months (experimental part 2.1), and to associate them with its meaningful referents by 16 months (experimental part 2.2).

Even if this framework seems to account for the phonotactic development found throughout this dissertation, further studies focusing in other phonotactic dependencies are needed to corroborate it and to enrich it. This work is just a small contribution to the understanding of infants' phonological development, however, there is still a long way to go…

Some loose ends to tie

Even if the present research offers evidence answering some of the questions addressed at the beginning of this work, many different questions raised by our findings will need to be explored in the future. First, further studies are required to explore 7-month-olds' preference for C-initial and C-final words found in experimental part 1.1. These studies will need to determine whether these preferences are due to sensitivity to the overall coronal frequency (coronals being overall more frequent than labials or velars) or to positional frequencies (coronals being more frequent in onset and coda word position). This is an important issue given that although most of the literature studying preferences for the more frequent structures has not found any evidence of consonant-based phonological acquisitions before 10 months of age (Werker & Tees, 1984; Best, McRoberts, & Sithole, 1988), it has been found that relative frequency of phonemes plays an important role in phonological development, infants acquiring frequent phonetic categories earlier than less frequent ones (Anderson, Morgan, & White, 2003).

Future research will also have to investigate the kind of non-adjacent phonological dependencies to which infants are sensitive to. Indeed, different phonotactic contrasts, including both consonants and vowels, need to be tested. Of particular interest, studies could explore possible differences between vocalic and consonantal dependencies, given the proposal of Nespor et al. (2003) and the infant results (Nazzi, 2005; Havy & Nazzi, 2009; Nazzi, et al., 2009) showing differences between consonant and vowel use in lexically-related processing, to the advantage of consonants. This issue has begun to be explored by Gonzalez-Gomez and Nazzi (2012, June). Indeed, we first found the existence of a posterior-anterior bias (corresponding to the prevalence of PA sequences over AP ones, such as *api* over *ipa*) in the French lexicon. Second, we conducted infant preference studies that showed the emergence of a preference for PA words over AP words between 10 and 13 months of age. Compared to our LC findings, this suggests a delay for the acquisition of non-adjacent vocalic dependencies, even though the strengths of the LC and PA biases are equivalent (63% for the LC bias and 72% for the PA bias). Further studies will be necessary to confirm such a delay, and to explore whether or not the PA bias or any other vocalic dependency can also constrain later lexical acquisition. Furthermore, future research is needed to investigate the kinds of constraints that apply to non-adjacent acquisitions, such as how distant can the dependents in the relation be.

In addition, the level at which phonological acquisitions operate requires further investigation to further specify whether or not these acquisitions operate at the level of phonetic categories, as suggested by the results of experimental part 1.2. To do so, other phonetic and phonotactic contrasts will have to be tested. A particular emphasis could be put on fricatives, given that infants showed a different performance pattern when presented with sequences of fricative consonants.

Furthermore, given the opposite bias found for plosive/nasal (LC) and fricative (CL) sequences, it will be necessary to explore what happens with mix sequences (i.e. sequences containing a plosive and a fricative consonant or a nasal and a fricative consonant) .

Concerning preterm infants' early language development, there is still a long way to go to understand the effects of prematurity on language acquisition (experimental part 1.3). First, further research will be needed to specify the language subdomains (prosodic acquisition, phonetic acquisition, segmentation, word learning, word production…) that might or might not be affected by preterm birth. Second, other phonetic and phonotactic contrasts will have to be tested, to determine whether or not phonetic and phonotactic development is really well preserved in preterm infants. Third, our study concentrated on a healthy population of preterms born between 26 and 33 weeks GA. Further studies will be needed to identify the characteristics of prematurity that impact language acquisition by testing larger and different samples of preterms (i.e. varying birth weight, gestational age, weight for their GA, presence of visible lesions, days in hospital…).

Moreover, our results with Japanese-learning infants (experimental part 1.4) raise different questions that will have to be addressed in future research. First, given that Japanese-adults show a perceptual CL bias (Tsuji, Gonzalez-Gomez, Medina, Nazzi, & Mazuka, in revision), older Japanese-learning infants should be tested to determine when in development they start having a perceptual CL bias. Moreover, our results highlight the importance of conducting crosslinguistic studies. Further crosslinguistic studies are needed to explore the emergence of the perceptual LC bias in other languages showing an LC bias in the lexicon (i.e. English, Estonian, German, Hebrew, Maori, Quechua, Spanish, c.f. MacNeilage, et al., 1999), and to test whether or not these early acquisitions can constrain early lexical development as well.

Accordingly, it will be necessary to further investigate the link existing between early speech perception and early lexical acquisition to determine, on one hand, the kind of phonological acquisitions that can influence word segmentation (experimental part 2.1) and/or word learning (experimental part 2.2). On the other hand, more studies will be required to explore how infants first process infrequent sequences. Our segmentation studies could not specify whether they mis-segment them, or whether these sequences are processed as bad exemplars, or whether infants recognize them but do not process them further. Finally, studies will be required to clarify how and when in development phonotactic effects on word acquisition change. All these and other possible questions deserve to be further investigated.

As this section shows, the present work offers more questions than answers, leaving lots of loose ends to be tied up in future studies.

Conclusion

To conclude, the present work has shown that by 10 months of age, infants are sensitive to non-adjacent phonological dependencies, as shown by the fact that French-learning infants have a preference for LC over CL sequences. This preference reflects the prevalence in the French lexicon of sequences starting with a labial consonant followed by a coronal one over the opposite pattern. In addition, our results suggest that these acquisitions operate at the level of consonants classes defined by manner of articulation, infants preferring LC structures for plosive and nasal sequences, but CL structures for fricative sequences.

Vis-à-vis the LC bias, our experimental results indicate that this bias is a result of the exposure to the linguistic input. It appears not to be solely due to direct articulatory constraints as previously suggested (MacNeilage, et al., 1999; 2000). This was evidenced by our babbling data and in the studies conducted with Japanese-learning infants and with preterm infants.

Furthermore, concerning preterm infants, we found that in terms of perception, the preterm 10-month-old pattern resembles that of the full-term 10-month-olds (same listening age) much more than that of the full-term 7-month-olds (same maturational age). We concluded that the developmental timing for phonotactic acquisition might be based on input experience, differing from the developmental timing previously found for prosody (Herold, et al., 2008; Peña, et al., 2010). Taken together, our results raise the possibility that neural immaturity might affect different language levels in different ways.

Finally, based on our results, we can conclude that early phonotactic acquisitions are used in early lexical development. Phonotactic properties influenced the segmentation of a word and the mapping of this word-like unit to a meaningful referent. Indeed, words with a frequent phonotactic LC structure were easier to segment and to associate with a referent, than words with an infrequent phonotactic CL structure. In other words, our findings add to the literature starting to show that early speech acquisition lays the foundations of early lexical acquisition.

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Appendix

“Those who know nothing
of foreign languages, know nothing of their own.”
Johann Wolfgang von Goethe

An analysis of the Japanese lexicon had shown that Japanese does not exhibit the LC bias found in other languages (MacNeilage, et al*.,* 1999). However, these results were based on a very small sample of words (68 words), preventing us from making any strong conclusions.

Before testing Japanese-learning infants’ preference for LC and CL structures we conducted different corpus analyses and adults experiments in order to reassess the findings of MacNeilage and collaborators (1999).

The results of the frequency analyses on two large adult corpora of Japanese are presented in the following paper. Additionally, it presents the results of a set of experiments testing Japanese adults’ perception and production of LC and CL sequences, as well as the perception of these sequences by French adults.

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(in revisión in Cognition).

The labial-coronal effect revisited: Japanese adults say pata, but hear tapa.

Abstract

The labial-coronal effect has originally been described as a bias to initiate a word with a labial consonant-vowel-coronal consonant (LC) sequence. This bias has been explained with constraints on the human speech production system, and its perceptual correlates have motivated the suggestion of a perception-production link. However, previous studies exclusively considered languages in which LC sequences are more frequent than their counterpart. The current study examined the LC bias in speakers of Japanese, a language that has been claimed to possess more CL than LC sequences. We first conducted an analysis of Japanese corpora that qualified this claim, and identified a subgroup of consonants (plosives) exhibiting a CL bias. Second, focusing on this subgroup of consonants, we found diverging results for production and perception such that Japanese speakers exhibited an articulatory LC bias, but a perceptual CL bias. The CL perceptual bias, however, was modulated by language of presentation, and was only present for stimuli recorded by a Japanese, but not a French, speaker. A further experiment with native speakers of French showed the opposite effect, with an LC bias for French stimuli only. Overall, we find support for a universal, articulatory motivated LC bias in production, supporting a motor explanation of the LC effect, while perceptual biases are influenced by distributional frequencies of the native language.

Keywords

Labial-coronal bias, Speech perception, Speech production, Perceptuo-motor interactions, Phonological tendencies.

1. Introduction

Some speech sounds and speech sound patterns are more frequent than others across languages. For instance, all languages archived by linguists possess plosives like /t/ and /d/ and syllables with a consonant-vowel (CV) structure, while not all languages possess plosives /p/ or syllables with CVC structure (cf. Locke, 2000; Maddieson, 1984). Such cross-language-commonalities have been attributed to biological restrictions on language production and perception on phylogenetic and ontogenetic scales (Locke, 2000; MacNeilage & Davis, 2000).

The labial-coronal (LC) bias describes a predominance of labial-coronal consonant sequences (e.g., /pata/) compared to coronal-labial ones (CL, e.g., /tapa/) in CVC or CVCV sequences (MacNeilage & Davis, 2000; MacNeilage, Davis, Kinney, & Matyear, 1999). This bias has been found in many languages, although it has been suggested that Japanese and Swahili might be exceptions (McNeilage, et al., 1999). It has also been found to influence infants' early words (MacNeilage, et al., 1999), and both adult speech production (Rochet-Capellan & Schwartz, 2007) and adult speech perception (Sato, Vallee, Schwartz, & Rousset, 2007). Given the pervasiveness of this bias especially in plosives, it was proposed to result from motor constraints of the human production system: the relative ease at producing LC sequences compared to CL sequences would translate into a higher frequency of LC sequences in the lexicon of most languages, and biases in both perception and production of these sequences.

In this context, and in spite of the dominating tendency for an LC bias in the languages investigated, Japanese has been pointed out as an exception to this pattern: MacNeilage et al. (1999) claimed that in Japanese, CL sequences occur more frequently than LC sequences (MacNeilage, et al., 1999). If this were true, this would suggest that motor constraints behind the LC bias could be modulated or even reversed in the lexicon of a language, which would then raise issues regarding how speakers of that language perceive and produce LC and CL sequences. This finding was, however, based on a very small sample of words. Therefore, the present research will first examine the distribution of LC and CL sequences in the adult Japanese lexicon based on two large samples of Japanese discourses (Corpus Analysis). These analyses will bring detailed information regarding the "exceptional" status of Japanese in terms of the LC bias. This will allow us, second, to explore if and how perception and production of LC and CL sequences are biased in adult speakers and listeners of this language, and use these data to evaluate the motor and perceptual explanations previously offered to explain the LC bias. Before presenting the results of our research, the remainder of the introduction will summarize previous research on the production and perception of LC and CL sequences.

1.1 The LC bias in production

The LC bias was initially reported in young children’s early productions. Ingram (1974) reported one English- and one French-learning infant’s tendency to initiate words with a labial consonant, followed by a consonant in posterior position. Similarly, Locke (1983) reported an "anterior-to-posterior progression" in young children's productions. Looking at a larger sample, MacNeilage et al. (1999) analyzed plosive /p, b, t, d/ and nasal /m,n/ segments in the first words of 10 English-learning infants, finding an LC bias in nine of them and an overall ratio of LC to CL sequences of 2.55. The prevalence of this bias across languages was confirmed in a review of seven studies focusing on infants' early productions in English, German, Dutch, French, and Czech (MacNeilage & Davis, 1998). A longitudinal analysis of five Dutch-learning children suggests that the early LC bias is associated with a certain developmental stage: Fikkert & Levelt (2008) report that Dutch children, as soon as they start combining consonants with different place of articulation features in production, go through a stage in which they preferably produce LC sequences.

This LC bias is also reflected in the inventories of languages. Lexicon counts of ten languages (English, Estonian, French, German, Hebrew, Japanese, Maori, Quichua, Spanish, and Swahili) revealed an overall ratio of LC to CL sequences of 2.23 (MacNeilage, et al., 1999). Except for Swahili and Japanese, the lexicon counts of all languages revealed a significantly higher frequency of LC compared to CL sequences, with only Japanese showing a trend in the opposite direction. However, the results obtained for some languages were based on very small samples of words. In particular, the Japanese data were based on 68 words extracted from a travel dictionary, which makes it necessary to reassess these results.

Several motor accounts have been proposed for the observed LC effect in language inventories as well as in language learning. The first one is based on the, possibly self-organizational, tendency of infants to start out an utterance with an easy element and then add complexity (MacNeilage & Davis, 2000). In the *frame-content* theory, a labial CV sequence is defined as the default, *pure frame* resulting from simple mandibular oscillation, while a coronal CV sequence or *fronted frame* requires an additional tongue movement. Alternatively, Rochet-Capellan & Schwartz (2007) proposed that LC sequences have a higher articulatory stability than CL sequences. Their criticism of the 'simple first' account includes that it is not clear if labial sequences are easier to produce than coronal ones (Vilain, Abry, Badin, & Brosda, 1999), and that a developmental explanation is not sufficient to explain the persistence of the LC bias in adult lexicons. In order to assess articulatory stabilities, French participants were asked to repeat LC and CL sequences (/pata/ and /tapa/, /pasa/ and /sapa/, /fata/ and /tafa/) in a speeded articulation task. The results first showed that speeding leads to a shift from one jaw cycle per syllable to one per disyllable through vowel reduction after one of the consonants, so that an initial CVCV sequence evolves into a CCV cluster (e.g., /pata/→/p'ta/). Second, shifts to an LC sequence like /p'ta/ were favored over shifts to a CL sequence like /t'pa/ for speeded LC and CL sequences (e.g., /pata/→/p'ta/; /tapa/→/p'ta/), suggesting a higher coordinative stability for LC compared to CL sequences.

While the above two accounts differ widely in the processes they suggest as the cause of the LC bias, they share the assumption that it is located in properties of the human speech production system. For this common assumption, a test of the sequence preferences in speakers of a language with different distributions would be crucial.

1.2 The LC bias in perception

Previous findings suggest that the articulatory stability of speech forms is coupled to their perceptual stability (Sato, Schwartz, Abry, Cathiard, & Loevenbruck, 2006). For example, the articulatory more stable CCV sequence /ps/+vowel shows a higher perceptual stability than the less stable CVC sequence /s/+vowel+/p/. These findings motivated the study of possible perceptual correlates of the LC bias (Sato, et al., 2007). To this end, the verbal transformation effect, a multistability perception phenomenon describing changes in perception during listening to the continuous rapid alternation of a speech form (Warren, 1961; Warren & Gregory, 1958), was exploited. For instance, while listening to rapid repetitions of the word "rest", listeners are likely to switch between perceiving it as a repetition of "rest" and “tress” or “stress” (Warren & Gregory, 1958).

French adults were presented with rapid repetitions of LC and CL sequences in voiceless (/p/, /t/), or voiced (/b/, /d/) plosive consonant contexts, and in the vowel contexts /a/, /i/, or /o/. Importantly, a lexical analysis showed an LC bias for plosives overall and for the subset of voiceless plosives, but a CL bias for voiced plosives, so that, from an input perspective, diverging perceptual biases were a possible outcome for these subsets. Hence, rather than being a consequence of motor constraints, the tendency to perceive LC rather than CL in the verbal transformation task might be a direct result of the input.

The ratio of time participants spent perceiving the sequences as LC or CL was calculated as an index of perceptual stability. Results showed that LC sequences were more stable than CL sequences for both voiceless and voiced plosives, thus did not reflect the input CL bias of voiced plosives. Such fine-grained difference in input thus did not reverse the LC preference of French listeners, and the authors interpret the results in the context of a perception-action link (e.g., Liberman & Whalen, 2000; Schwartz, Basirat, Ménard, & Sato, in press), suggesting that the articulatory advantage of LC chunking is connected to its perceptual chunking.

However, an influence of input on the LC bias as an alternative explanation can not be discarded: The LC bias in French is true both overall but also restricted to sequences of all plosives in French (Sato, et al., 2007; Vallée Rousset & Boë, 2001), and this strong bias could override the very local CL bias restricted to voiced plosives. This would be in line with numerous studies showing that ambient language structures affect segmentation, both in studies of natural language segmentation (e.g., McQueen, 1998; Weber & Cutler, 2006), or artificial language segmentation (e.g., Mersad & Nazzi, 2011; Pena, Bonatti, Nespor, & Mehler, 2002; Saffran, Newport, & Aslin, 1996). These ambient language influences can also be observed in infants, who start preferring to listen to words with legal over illegal phonotactic patterns in their native language (e.g., Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Friederici & Wessels, 1993), and frequent over infrequent speech sound sequences (Jusczyk, Luce & Charles-Luce, 1994) between 6 and 9 months of age.

Taking this input-based alternative into account, Nazzi et al. (2009) tested the LC bias in French-learning infants of 6 and 10 months of age. In a head-turn preference paradigm (HPP), infants were tested on their preference for lists of LC vs. CL CVCV sequences that included both voiceless and voiced plosives, showing they preferred the LC lists at 10, but not 6, months. These results strongly suggest that language input might play a role in infants' development of a perceptual LC bias. This finding was extended to CVC sequences, showing the emergence of an LC bias between 7 and 10 months of age (Gonzalez-Gomez & Nazzi, 2012). In both infant studies, as in Sato et al. (2007), plosive consonants were used. In order to extend these findings to other manners of articulation and to further explore the level on which input biases influence perception, Gonzalez-Gomez & Nazzi (in preparation) later explored the presence of the LC bias in the adult lexicon at a more fine-grained level. After establishing that the overall LC bias is found on sequences restricted on two manners of articulation (sequences of plosives and sequences of nasals) but not on sequences of fricatives, they tested French-learning 10-month-olds on LC versus CL preferences for the three different manners of articulation separately. The results showed an LC bias for plosives and nasals, and the opposite CL bias for fricatives, lending further support to an input-based origin of the LC bias in perception (but see Rochet-Capellan & Schwartz, 2007, for a discussion of motor specifities that could lead to differences between plosives and fricatives) that is learned at the level of classes of consonants defined by manner of articulation.

The above findings underline the importance of further exploring the LC bias, at different ages (infants, adults), in different languages (that have an overall LC bias, as all languages studied so far, or that have been proposed to have an overall CL bias), and possibly also for different classes of consonants. In particular, in order to tease apart the motor and perceptual explanations, it appears important to test the LC bias in cases in which the adult input has a CL bias either overall or in the subset of plosives, since this is the manner that has been discussed most extensively in the context of an LC bias (cf. MacNeilage, et al., 1999; Sato, et al., 2007). In such a case, motor explanations still predict an LC bias while perceptual explanations predict a CL bias like observed in the subgroup of voiced plosives (Sato, et al., 2007) and fricatives (Gonzalez-Gomez & Nazzi, in preparation) in French. The present study was intended to start testing such cases in Japanese adults.

1.3 Aims of the current study

The current study assesses articulatory and perceptual biases in adult speakers of Japanese. As a first step, the trend towards a dominance of CL over LC sequences in the adult lexicon (MacNeilage, et al., 1999) was reassessed by analyses of large corpora of Japanese (see section 2. Corpus Analysis). Given the results by Gonzalez-Gomez and Nazzi (in preparation), these analyses were conducted either overall, or separated by manner of articulation. Based on our findings, we subsequently studied Japanese adults' articulatory and perceptual preferences for LC versus CL sequences for a subset of consonants that exhibits a CL bias in the adult lexicon.

In order to compare our results to previous studies, the design of the production study (Experiment 1) was closely matched to Rochet-Capellan & Schwartz (2007). The perceptual experiment was also closely matched to Sato et al. (2007). However, we extended it by using a fully crossed design (presenting Japanese adults with stimuli recorded by a Japanese speaker and stimuli recorded by a French speaker in Experiment 2, and then presenting French adults with the same stimuli in Experiment 3) in order to explore possible effects of language of presentation, and to replicate the previous results in French with our new set of stimuli. Experiment 4 addresses some possible interpretations with regard to language-of-presentation effects found in Experiment 2 and 3.

If the LC biases found in production and perception are due to articulatory factors, then Japanese participants are expected to show a higher articulatory stability of LC compared to CL sequences, and both Japanese and French adults should show an LC preference in perception. However, if preferences are influenced by input properties, because the consonants tested have a CL input bias in Japanese but an LC input bias in French, Japanese participants are expected to show a CL bias both in production and perception, while French participants should have a perceptual LC bias. Note that while the above predictions are made for both production and perception, it remains possible that dissociations will be observable, the present study being the first one to try to directly articulate the link between input properties, production and perception biases in determining the LC bias.

2. Corpus Analysis

In order to reassess the findings of MacNeilage and Davis (2000) that Japanese has a higher frequency of CL compared to LC patterns, two large adult corpora of Japanese were analyzed.

Given the manner of articulation effects found in the developmental studies by Gonzalez-Gomez and Nazzi (in preparation), we conducted a series of analyses with all manners together, and two other series of analyses restricted to either plosives or nasals. The reason for not exploring distributions of the other manners or articulation independently was firstly practical, since the other manners in Japanese do not allow labial consonants. Secondly, the LC effect has originially and predominantly been assessed with plosives and nasals (i.e., Mac Neilage, et al., 2000; Sato, et al., 2007), as these are the first sounds produced by infants. Therefore, looking at the patterns for this subgroup separately is especially important.

2.1 Input corpora

As a corpus of written language, the NTT frequency corpus (Amano & Kondo, 2000) was chosen, which contains all written content of the Asahi Newspaper, a major Japanese daily newspaper, over 14 years (1985-1998). The original written text includes the three Japanese script types *kanji, hiragana* and *katakana*, as well as some alphabetic scripts. Katakana transcriptions for all forms except the alphabetic scripts are provided, which allowed us to do an unambiguous phonemic transcription of the segments of interest.

As a corpus of spoken language, the subsection ‘simulated public speech’ of the Corpus of Spontaneous Japanese (CSJ) (Maekawa, 2003) was chosen. It includes speech of 590 participants holding a 10-12-minute speech on an everyday topic in front of a small audience. The corpus used for the analyses, includes phonemic transcriptions by trained phoneticians.

The target consonants for the analyses of all manners were labial (p, b, m, f, v) and coronal (t, d, n, s, z, ʃ, tʃ, j, r) segments. Note that the labial segments (f, v) are very low-frequency segments (with the exception of /f/ in front of the vowel /u/, they appear exclusively in recent loanwords). For the analyses of plosives, we used labial (p, b) and coronal (t, d) plosives, and for the analyses of nasals, we used labial (m) and coronal (n) nasals. All CVC sequences were analyzed regarding the token frequencies of LC and CL sequences. Frequencies were computed three different ways: Firstly, any CVC sequence within a word was considered (ANY), secondly, only word-initial CVC sequences were considered (INI), and finally, only CVCV words were counted (WORD).

2.2 Results and Discussion

Results of the analyses are presented in Table 1. Chi-square tests were conducted to test for the significance of the differences between LC and CL occurrences.

The first remarkable finding is that overall, very similar results are obtained for the two corpora, which suggests that the effects found are robust. Indeed, the few differences observed are due to differences in the size of the biases, while the direction of the biases observed is always the same across the two corpora. Second, it also appears that the results are not affected by the positions/structures of sequences we analyze, since similar results are found whether the analyses are performed anywhere within a word (ANY), word-initially (INI), or in words with a CVCV structure (WORD). This suggests that the constraints that apply to labial and coronal sequences are very strong and independent of their position with respect to word boundaries.

Table 1. Token frequencies, ratios and chi-square tests of plosive, nasal and all LC and CL sequences in the NTT and CSJ corpora.

		ANY		**INI**		**WORD**	
		NTT	**CSJ**	**NTT**	**CSJ**	**NTT**	**CSJ**
Plosives	LC	437,106	3,015	137,607	1,360	9,627	94
	CL	567,420	7,682	236,449	5,264	103,975	2156
	Ratio	0.77	0.39	0.58	0.26	0.09	0.04
	χ^2	202,697.0	4,331.8	134,382.6	5,745.6	4,820,689.6	1,978.7
	p	<.001	<.001	<.001	<.001	<.001	<.001
Nasals	LC	7,681	28,038	2,702,830	23,837	802,292	12,480
	CL	4,315	4,572	328,112	2,879	152,237	971
	Ratio	1.78	6.13	8.24	8.28	5.27	12.85
	χ^2	2,625.7	120,440.3	17,187,075.1	152,566.1	2,775,747.7	136,413.2
	p	<.001	<.001	<.001	<.001	<.001	<.001
All manners	LC	20,762,465	211,897	13,276,873	156,841	6,298,998	105,756
	CL	11,209,479	84,867	5,594,640	44,662	3,086,723	12,199
	Ratio	1.85	2.50	2.37	3.51	2.04	8.67
	χ^2	123,780,844.4	1,119,548.5	131,252.8	2,624,008.5	293,129,772.5	2,732,623.2
	p	<.001	<.001	<.001	<.001	<.001	<.001

Regarding the bias itself, it is noteworthy that our findings do not support the claim by MacNeilage et al. (1999), based on a very small sample of 68 Japanese words, that Japanese is a language with a CL bias. On the contrary, it appears that, overall, Japanese is a language with an LC bias, like most other languages reported so far.

However, the overall bias translates differently for the two manners of articulation on which restricted analyses could be conducted. For nasals, the LC to CL ratios were above 1 for both corpora and for the ANY, INI and WORD analyses, with significant differences between frequencies of LC and CL occurrences. But for plosives, the LC to CL ratios were below 1 for all 6 comparisons, indicating a higher frequency of CL compared to LC sequences. Chi-square tests indicate that the difference between LC and CL frequencies are statistically significant for all comparisons.

In summary, the adult Japanese lexicon thus has an overall LC bias, while a CL bias was found but only restricted to sequences of plosives. On the one hand, these results support the notion of a universal LC bias, and Japanese is no exception to this pattern. On the other hand, Japanese deviates from this overall pattern with regard to plosives[5]. As this is the manner that has been focused on in previous studies on the LC bias (MacNeilage, et al., 1999; Sato, et al., 2007), Japanese is, despite its lack of an overall LC bias, an ideal test case for the current research, because it shows a CL bias in the most critical manner. Given these findings, and since we were interested in determining Japanese adults' articulatory and perceptual preferences in cases in which there was a CL bias in the input, for which motor and perceptual explanations of the LC bias make different predictions, the remainder of our study focused on comparing Japanese adults’ production and perception of LC and CL sequences restricted to plosive consonants.

3. Experiment 1: Production

This experiment assesses the relative articulatory stability of plosive LC versus CL disyllables in speakers of Japanese. A previous study in French found that the speeded production of LC and CL plosive CVCV sequences evolves more frequently towards CCV sequences with an LC consonant cluster than towards one with a CL cluster (Rochet-Capellan & Schwartz, 2007). Since for plosives, and contrary to French, we found that CL sequences are more frequent than LC sequences in Japanese, it was of interest if a similar LC articulatory pattern would be found for Japanese adults (motor interpretation), or whether they would show a CL bias (perceptual interpretation). Procedure and analysis were closely matched to Rochet-Capellan and Schwartz (2007).

3.1. Participants

Nineteen undergraduate students (seven females) of a Japanese university in the Tokyo area with a mean age of 19.7 years (range: 19-22) participated in the experiment for payment. All speakers were native speakers of Japanese without speech or hearing problems.

3.2. Stimuli

The phonetic material to be produced consisted of four LC (/pata/, /pete/, /piti/, and /putu/), and four CL (/tapa/, /tepe/, /tipi/, and /tupu/) CVCV disyllables. While Rochet-Capellan and Schwartz (2007) employed plosive and mixed plosive-fricative consonants in the vowel context /a/, we restricted our stimuli to the plosive manner of

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[5] While in French, the overall LC bias was found also on the analyses restricted to plosives and nasals, but was reversed for fricatives (Gonzalez-Gomez & Nazzi, in preparation).

articulation for two reasons: because a CL advantage was only found restricted to plosives in Japanese, and because there are no labial fricatives in Japanese. Given this, and in order to maintain some variation, we introduced different vowel contexts instead. The disyllables /pata/ and /poto/ are meaningful in Japanese (both are onomatopoeic expressions; “patapata” expresses the sound of footsteps, and “potopoto” the sound of dripping liquid), and therefore we decided to exclude /poto/ and its counterpart /topo/. However, we included /pata/ and /tapa/, because the vowel /a/ is the only one that allows a direct comparison with the previous study, and it allows the most open mouth configuration (MacNeilage, Davis, Kinney, & Matyear, 2000).

3.3 Procedure

Participants were seated in front of a laptop computer (IBM ThinkPad X 40) connected to a USB microphone (Sony CARDIOID Dynamic Microphone F-V810). In each trial, participants were first presented a disyllable written in Japanese kana script, e.g. パタ /pata/ in black on white background in the middle of the screen. They were instructed to repeat the sequence presented, accelerating and decelerating in the rhythm of a visual timer they initiated by pressing the ‘Space’ key. The timer consisted of an alternation of black and white squares in the middle of the screen. It had a total duration of 16 seconds with an acceleration phase of eight seconds, followed by a deceleration phase of the same length. The duration of presentation of each square started at 300 ms and gradually decreased until reaching 125 ms at four seconds, and 50 ms at eight seconds. After that, durations again gradually increased symmetrically to acceleration. The timer was preceded by a blue square for 1000 ms. Participants were instructed to produce the first syllable on the black square, the second on the white, and so on. The visual timer did not have the function of precisely coordinating participants’ production speed, but rather served as a global marker in order to decrease variability and to push participants to their limits. Participants were told that the timer would at one point reach an almost impossible speed, and that they should try to keep their production speed as fast as possible during that phase. Participants were encouraged to take a rest between trials whenever necessary, and there was a break between each block. There were six practice trials, during which the experimenter was present and made sure participants had understood the instructions. Productions for each trial were recorded as separate sound files on the computer hard disk.

There were three experimental blocks during each of which the eight CVCV disyllables were presented once. Presentation order within each block was randomized independently.

3.4. Analysis

In order to assess if CVCV sequences would asymmetrically evolve into LC or CL CCV clusters, prosodic measurements based on vowel intensity were conducted. Analyses concentrated on the 3 seconds following the point of maximum acceleration, since Rochet-Capellan and Schwartz (2007) showed that articulatory asymmetries were most likely to occur in disyllable productions (hereafter, “utterances”) of 300 ms or faster. 67 % of utterances in the selected time-span fulfilled this premise (M = 173 ms, min = 50 ms, max = 400 ms).

In general, the first production of each participant for one stimulus type was analyzed. If less than 50% of the participant’s first production was codable for CV alternations (see below for exclusion criteria), the second production was chosen instead, and if this was still not codable, the third. A participant’s second production was chosen in 4.6%, and the third in 0.6% of cases.

Intensity of each produced sequence was continuously estimated with the PRAAT software (Boersma & Weenink, 2009) using a 42.6 ms Kaiser-20 window with side-lobes below -190 decibel. Maxima and minima were automatically detected by consecutively searching time windows of 80 ms for their intensity maxima and minima from the beginning to the end of each 3-second sound file. The alternation of plosive consonants and vowels mostly led to clear minima and maxima in the resulting energy curves, with minima representing the complete closure in plosives, and maxima the vowel peaks. Manual parallel inspection of spectrograms and sound file ensured that no minimum and maximum value was missing or tagged twice.

Subsequently, the minima were manually labeled as either /p/ or /t/ by parallel inspection of spectrograms and sound files wherever possible. When a pattern evolved towards a CC cluster as /pt/ or /tp/ without any vowel peak in between, the corresponding minimum was labeled such. As the fast speed of some productions occasionally resulted in a deviation from the instructed voiceless /p/ or /t/, the labeling rule was that minima were labeled as /p/ or /t/ as long as a labial or coronal closure was clearly identifiable. This included voiced stops (/b, d/) or affricates (/pʃ/, /tʃ/), but excluded all other manners of articulation. Non-identifiable productions and speakers’ errors, such as pauses, breathing, or repetition of the same CV sequence, were excluded from analysis. Overall, 12.6% of total productions were excluded this way.

As an index for articulatory asymmetry, the difference between the intensity scores of the vowel following a labial (V_L) and coronal (V_C) consonant was calculated for each utterance according to the formula: Delta I = $I(V_C)-I(V_L)$. A Delta I close to zero indicates a symmetrical utterance with similar intensities for the vowel after the labial and coronal consonants, while a positive value indicates a tendency for /pt/ CC clusters, and a negative value for /tp/ CC clusters. Mean Delta I values were obtained for each utterance, resulting in eight delta values for each of the 19 participants to be subjected to analysis. Among these, two utterances (/putu/ for one participant, and /tupu/ for another) only contained coronal consonants or non-identifiable productions and thus did not contribute any Delta I values to analyze.

3.5 Results and Discussion

Figure 1 plots Delta I values for each stimulus type against utterance duration. Although most utterances center around zero, a visual inspection of the graphs shows that for utterances faster than 300 ms there are more positive than negative Delta I values.

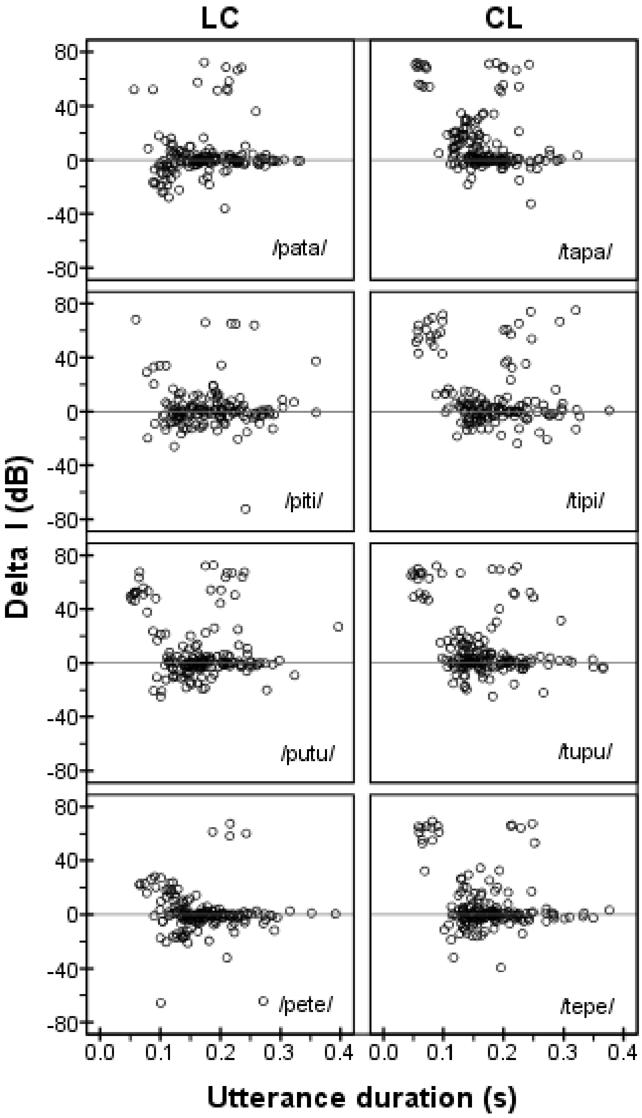

Figure 1. Y axis: Intensity variation between the vowel after the labial consonant and the vowel after the coronal consonant (Delta I). Positive values indicate /pt/ clusters, negative values indicate /tp/ clusters. X axis: Duration of the respective utterance. Each circle represents one utterance.

This asymmetry was statistically evaluated in two ways. First, a Chi-square test was conducted to compare frequencies of positive and negative Delta I means, showing that there were overall significantly more positive means than negative means (cf. Table 2). Second, a one-sample t-test was conducted to evaluate if Delta I means were significantly different from 0, showing that this was the case (cf. Table 2). To make sure that the lexical nature of /pata/ did not bias the results into the labial-coronal direction, the analyses were repeated after the exclusion of the disyllables /pata/ and /tapa/, which did not affect the direction of results (cf. Table 2).

Lastly, analyses by token showed that Delta I is positive for all stimuli, with more positive than negative means for all stimuli (cf. Table 3; the value closer to zero is found for /pete/).

Table 2. Mean Delta I values, number of positive and negative means, and statistical analyses for disyllables overall and under exclusion of the /a/ vowel context. χ^2–test compared the number of negative and positive means. A positive Delta I value indicates evolvement towards an LC cluster. One-tailed t-test compared mean Delta I against 0.

				χ^2 – test		t-test	
	Mean Delta I	Negative means	Positive means	χ^2 (df)	*p*	t (df)	*p*
All disyllables	5.20	54	96	11.76	.001	4.78 (149)	<.001
Disyllables excluding pata/tapa	4.68	40	72	9.14	.002	3.71 (111)	.001

Table 3. Mean Delta I values and number of positive and negative means by token. Positive Delta I values indicate evolvement towards an LC cluster, and negative means indicate evolvement towards a CL cluster.

	pata	tapa	piti	tipi	putu	tupu	pete	tepe
Mean Delta I	4.05	9.42	1.07	8.49	5.80	8.65	0.31	4.04
Negative means	8	6	9	6	6	4	9	6
Positive means	11	13	10	13	12	14	10	13

In summary, the current experiment shows higher articulatory stability of LC compared to CL plosive sequences in native Japanese adult speakers despite the fact that in the lexicon of their native language, there are more CL plosive sequences than LC plosive sequences. As such, these results appear in line with an explanation of the LC bias based on articulatory factors. Note however that a perception-based explanation cannot entirely be ruled out if the LC production bias is determined by overall bias, i.e. an input bias based on all segments rather than based on plosives alone, which our corpus study revealed is also LC in Japanese. Before further discussing the implications of these results, we first present an experiment exploring if and in which direction the perception of LC and CL plosive consonant sequences by Japanese speakers is biased.

4 Experiment 2: Perception in Japanese Adults

To examine whether perception, like production, follows the universal tendency of an LC bias, or if the input frequency of the native language influences perceptual preferences, a verbal transformation task was conducted with Japanese participants. The experimental design and procedure closely resembled Sato, Vallee, Schwartz and Rousset (2007). We focused on plosive consonants since the motor and perceptual explanations predict different outcomes (LC versus CL biases respectively), and decided to present each participant with stimuli recorded by a Japanese speaker and by a French speaker in order to determine potential effects of the phonological/phonetic properties of the stimuli.

4.1 Participants

Sixteen students and university staff (seven females) of several universities in Tokyo (mean age: 24.2 years; range: 20-38) with no speaking or hearing problems participated in the experiment for payment. They were all native speakers of Japanese. Due to a program error, four additional participants were tested but they were not presented with the full set of stimuli. The data from these participants were therefore excluded from analysis.

4.2 Stimuli

The target sequences used here were the same as in Experiment 1, excluding the vowel context /a/: three LC sequences (/pete/, /piti/, /putu/) and their CL counterparts (/tepe/, /tipi/, /tupu/). These sequences differ from those in Sato et al. (2007) in two ways. First, instead of presenting sequences in the vowel contexts /a, i, o/, we chose the vowel contexts /e, i, u/, because /pata/ and /poto/ are lexical in Japanese (cf. section 3.2). Note that while in the production study, we did not exclude /a/ in order to keep one stimulus constant with the previous study in French, we could exclude it in the present perception study since the vowel context /i/ was used by Sato et al. (2007). As a second change, we presented stimuli recorded by native speakers of two languages: a male native speaker of Tokyo Japanese, and a male native speaker of metropolitan French.

In order to obtain the stimuli, several tokens of the CV sequences /pe/, /pi/, /pu/, /te/, /ti/, /tu/ were recorded in isolation in a soundproof room. Both speakers were instructed to pronounce CV sequences at a natural conversation rate while keeping an even intonation and intensity. The items were digitized on the hard disk of a computer at a 44.1 kHz sampling rate. Then, for each language and for each vowel context, one p-initial and one t-initial CV sequence (e.g., /pe/ and /te/ in French) were selected to form one token pair. Consonant and vowel duration, mean consonant and vowel intensity, F1, F2, and F3 formant values, as well as minimum, maximum, and mean vowel pitch were matched as closely as possible within each token pair (Table 4). From each of these token pairs, two experimental stimulus file were constructed, both consisting of 300 alternated repetitions of the two syllables, one starting with the p- and the other one with the t-inital CV sequence. This resulted in a total of twelve stimulus files (3 vowel contexts x 2 initial CVs x 2 voices).

In order to reflect the silent period before stop release, a 100 ms pause preceded each CV sequence. On average, Japanese token pairs were 588 ms long,and French token pairs were on average 607 ms long.

Table 4. Acoustic properties of presented CV syllables. Acoustic properties were matched as closely as possible for each CVCV pair. Consonant duration reflects voice onset time (VOT) plus the added 100 ms of silence.

		Japanese					
		/pe/	/te/	/pi/	/ti/	/pu/	/tu/
Duration *(ms)*	Consonant	126	137	156	159	130	146
	Vowel	156	159	158	156	137	141
Intensity *(dB)*	VOT	71	71	63	68	71	72
	Vowel	77	77	75	77	77	80
Vowel formant *(Hz)*	F_1	577	577	376	375	335	376
	F_2	2189	2269	2471	2471	1786	1786
	F_3	2793	2793	3398	3317	2471	2552
Vowel pitch *(Hz)*	min	90	90	100	103	91	93
	max	139	146	136	150	126	127
	mean	110	110	111	112	104	108
		French					
Duration *(ms)*	Consonant	130	145	148	170	144	153
	Vowel	143	158	133	160	148	156
Intensity *(dB)*	VOT	68	64	63	66	67	65
	Vowel	72	72	73	73	72	73
Vowel formant *(Hz)*	F_1	385	344	324	283	335	375
	F_2	1945	1924	2026	2046	1061	1141
	F_3	2613	2573	2876	2795	2753	2713
Vowel pitch *(Hz)*	min	100	93	98	110	100	99
	max	117	117	130	116	121	136
	mean	107	103	113	113	111	108

4.3 Apparatus and Procedure

Participants were individually seated in front of a laptop computer (IBM ThinkPad X 40) in a sound-attenuated room and presented the experimental stimuli binaurally via a pair of headphones (audio-technica ATH-A 500) at a comfortable sound level. Different from Sato et al. (2007), participants did not respond orally as soon as they perceived a change, but pressed response keys instead. This procedure was chosen, because in contrast to previous studies on verbal transformations (Pitt & Shoaf, 2002; Sato, et al., 2007; Warren, 1961), which had the additional purpose of exploring the space of possible transformations, the current study was solely interested in the ratio of LC to CL perception. As such, oral responses including the exact nature of each transformation were not necessary.

On a QWERTY laptop keyboard, the "I" and "O" keys were covered with stickers clearly labeled as "P" and "T". Participants were asked to press the left key with the index finger, and the right with the middle finger of their right hand. The labeling of keys was counterbalanced across participants, so that for half of the participants “P” was left of “T”, and "T" was left from "P" for the other half. The "G" key was covered with an unlabeled blue sticker.

Participants were first introduced to the phenomenon of verbal transformations by listening to a repeated sequence of either the disyllable /mono/ or /nomo/ (counterbalanced across participants). After listening, they were asked if they had perceived any change in the sequence, and in case not, they were explained that their perception of the sequence might change from /mono/ to /nomo/, or vice versa, during listening. In the subsequent practice trial, they listened to the same sequence for about one minute, and were instructed to press response keys as follows. They were asked to initiate the trial by pressing the space key, and to press either the “N” or “M” key as soon as the sound sequence had started in order to indicate whether they had perceived /n/ or /m/ at the beginning of the sequence. Subsequently, they were asked to press the response keys only if perceiving a change. If they perceived a change from /mono/ to /nomo/, they were asked to press “N”, and vice versa. It was emphasized that they might not perceive any change, or else very frequent changes from time to time. They were also told that they might perceive a change to a completely different sequence including neither /m/ nor /n/, and to press the blue key in this case. This option was included based on the findings of Sato et al. (2007; Experiment 1) that a change to a different sequence was perceived in 31% of trials.

At the beginning of each trial, a fixation cross appeared for 500 ms, followed by a blank screen for the duration of the sound sequence. After the practice trial, participants were explained that sequences would now start with either /p/ or /t/ instead of /m/ or /n/. After each of the twelve trials, a screen informed participants about the number of trials completed and encouraged them to rest as long as necessary. Trial order was randomized across participants. The experiment was run with E-Prime 2.0, and answers were saved on the hard disc of the computer.

4.5 Results and Discussion

Percentages of LC, CL and other responses for the 12 different experiment files are presented in Figure 2.

Perceptual stability of each stimulus was obtained by summing up the time the initial disyllable was perceived (LC for p-initial sequences and CL for t-initial sequences) as indicated by button presses. Then, relative perceptual stability (our dependent variable) was obtained by dividing the perceptual stability of each stimulus by the total time the stimulus was perceived as either LC or CL. Overall, the time spent perceiving a stimulus as either an LC or a CL pattern was 90.5% for Japanese sequences, and 90.4% for French sequences, showing that for stimuli of both languages, the recognition rate was similarly high.

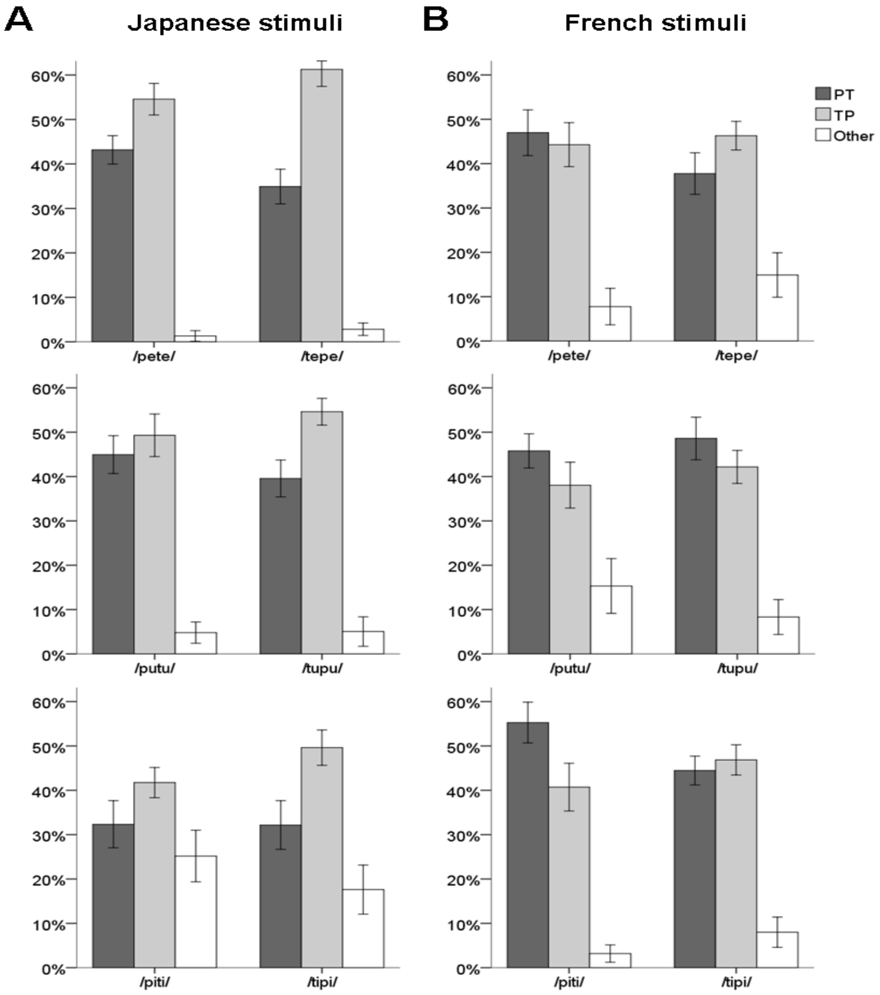

Figure 2. Mean ratios of perception as LC or CL sequence for Japanese participants. (A) Stimuli presented in Japanese (B) Stimuli presented in French. Error bars represent +/- 1 SE.

A three-way repeated-measures ANOVA with the within-subject factors of Sequence (LC versus CL), Language Presented (Japanese versus French) and Vowel (e, i, u) was performed. Bonferroni-corrected post-hoc paired comparisons at a significance level of $p < .05$ were conducted where appropriate. This analysis revealed a significant main effect of Sequence [$F(1, 15) = 6.02$, $p = .027$, $\eta^2_p = .286$], indicating higher perceptual stability for CL sequences ($M = 0.57$, $SD = 0.11$) than for LC sequences ($M = 0.50$, $SD = 0.07$). There was also a significant interaction between Sequence and Language Presented [$F(1, 15) = 8.232$, $p = .012$, $\eta^2_p = .354$]. Post-hoc paired comparisons showed that the effect of Sequence was significant for Japanese stimuli ($p = .004$; stability of CL sequences: $M = 0.62$, $SD = 0.13$; stability of LC sequences: $M = 0.44$, $SD = 0.12$), but not for French stimuli ($p = .336$; stability of CL sequences: $M = 0.52$, $SD = 0.12$; stability of LC sequences: $M = 0.56$, $SD = 0.12$). This indicates a CL bias for Japanese stimuli, and no bias for French stimuli.

The results show an overall CL bias for native speakers of Japanese, which is congruent with perception-based predictions since there is a CL bias for plosive sequences in the Japanese lexicon. These results complement the previous results in French (Sato, et al., 2007), in which an LC bias was found for plosive and mixed plosive-fricative sequences that exhibit an LC bias in the French lexicon. This suggests effects based on input properties. However, the effect observed in our experiment was influenced by language of presentation, such that a CL bias occurred for Japanese stimuli, but not for French stimuli. Since it was unclear whether this language effect was due to some idiosyncratic properties of the stimuli recorded, or whether they reflected language-specific processing effects, we decided to replicate Experiment 2 with French participants.

5. Experiment 3: Perception in French Adults

Experiment 3 tested perceptual biases in French participants with the same stimuli as those presented to Japanese participants in Experiment 2.

5.1 Participants

Sixteen students and university staff (12 females) of Université Paris Descartes (mean age: 26.3 years; range: 22-44) with no speaking or hearing problems participated in the experiment for payment. They were all native speakers of French.

5.2 Stimuli

The stimuli were the same as in Experiment 2. As the stimuli were primarily constructed for the study of Japanese participants, it could not be avoided that of these, /pete/, /piti/, and /tipi/ were very low frequency words in French. The word corresponding to /pete/ is “péter”, meaning “to fart”, with a frequency of 17.09, the word corresponding to /piti/ is **“**Pythie,**”** the Greek oracle, with a frequency of 0.54, and the word corresponding to /tipi/ the native American tent **“**teepee”, with a frequency of 0.01. Frequencies are according to counts in Lexique.org (New, Pallier, Ferrand, & Matos, 2001).

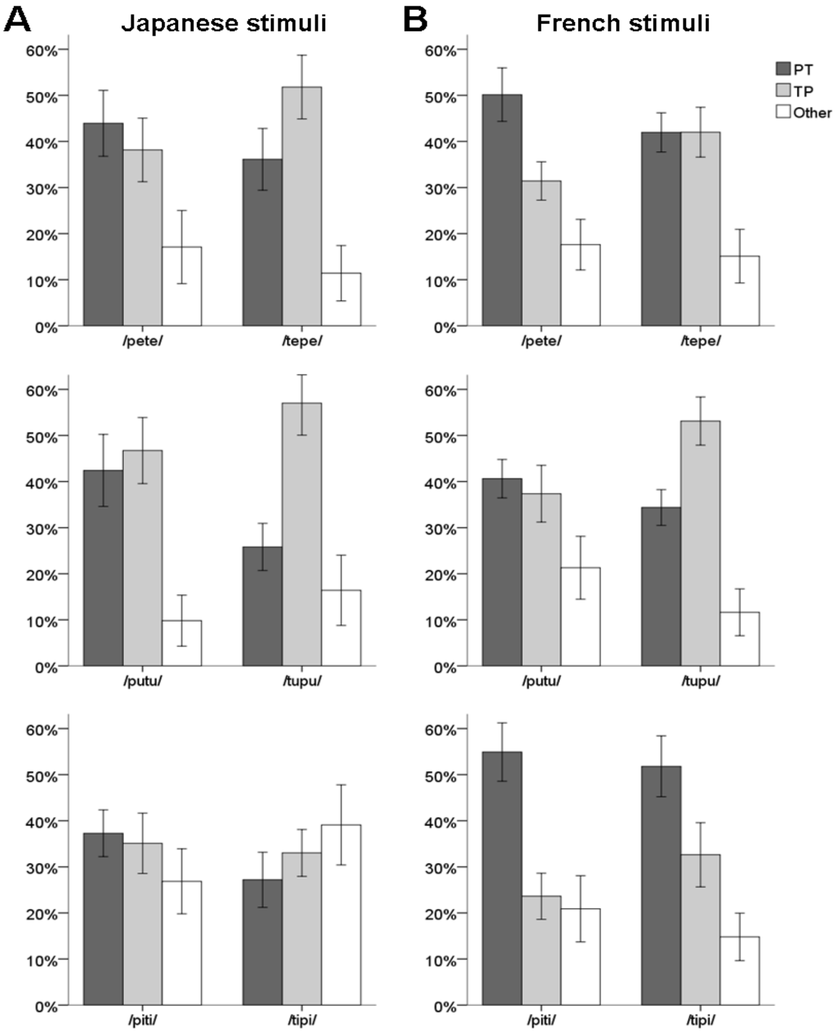

Figure 3. Mean ratios of perception as LC or CL sequence for French participants. (A) Stimuli presented in Japanese (B) Stimuli presented in French. Error bars represent +/- 1 SE.

5.3 Procedure

The procedure was the same as in Experiment 2.

5.5 Results and Discussion

Percentages of LC, CL and other responses for the 12 different experiment files are presented in Figure 3. The time spent perceiving a stimulus as either LC or CL was 80.0% for Japanese sequences, and 83.1% for French sequences.

As in Experiment 2, a 3-way repeated-measures ANOVA with the within-subject factors of Sequence, Language Presented and Vowel was performed. Due to a violation of the sphericity assumption in the interaction between Sequence and Vowel, Greenhouse-Geissner corrected values are reported for this interaction. There was no main effect of Sequence [F(1, 15) = 0.41, p =. 531, η^2_p = .027; stability of CL sequences: M = 0.56, SD = 0.12; stability of LC sequences: M = 0.58, SD = 0.10]. However, there was a significant interaction between Sequence and Language Presented [F(1, 15) = 7.93, p = .013, η^2_p = .346]. Post-hoc paired comparisons showed a significant LC bias for French stimuli (p = .008; stability of CL sequences: M = 0.49, SD = 0.15; stability of LC sequences: M = 0.63, SD = 0.13), but no significant effects for Japanese stimuli (p = .119; stability of CL sequences: M = 0.63, SD = 0.15; stability of LC sequences: M = 0.53, SD = 0.17). There was also a significant interaction between Sequence and Vowel [F(1.47, 21.97) = 5.23, p = .021, η^2_p = .258]. The difference in stability between sequences was significantly different for the vowels /u/ (p = .037; stability of CL sequences: M = 0.64, SD = 0.14; stability of LC sequences: M = 0.52, SD = 0.16) and /i/ (p = .020; stability of CL sequences: M = 0.49, SD = 0.22; stability of LC sequences: M = 0.63, SD = 0.14), with a CL bias for the former, and an LC bias for the latter.

In summary, although French participants did not show a main effect of sequence, this lack of an overall effect is due to the fact that we presented stimuli recorded in either French or Japanese, the former giving rise to an LC bias and the latter giving rise to no bias. The LC effect for native language stimuli thus replicates the previous findings (Sato, et al., 2007), extending them to new sequences and new recordings.

Interestingly, both the vowel context and language of presentation matter for French participants. The former was not found in Experiment 2 for Japanese participants, and although it is unclear why there was such an unpredicted CL bias for the /u/ vowel context, a possible explanation comes from informal observations given after the task by some participants, who declared having perceived “tu peux” (you can), probably as a misperception of the /tupu/ and /putu/ sequences. This misperception, which appears slightly larger for the Japanese stimuli, might have been favored by phonetic properties of the /u/ vowel in Japanese, which is pronounced with compressed lips, is unrounded but without spreading (Okada, 1991). As such, it is different in realization from the French /u/ (Vance, 1987).

As for the language of presentation effect, French participants' perceptual bias turned out exactly opposite from that of Japanese participants, with an LC bias for native stimuli only. Not only do we thus confirm the validity of our French stimuli by replicating Sato et al. (2007), but we also find an interesting crossed result with a perceptual bias consistent with native language input for both Japanese and French listeners, thus a CL bias for Japanese participants and an LC bias for French participants, but with native stimuli only. This, firstly, confirms that perceptual input influences perceptual biases, and secondly raises the question of why these respective biases disappear in non-native stimuli.

A first possibility are idiosyncratic characteristics of the stimuli that could have led to the dominant perception of LC sequences for the French, and CL sequences for the Japanese stimuli, disregardless of listeners' native language biases. As the stimuli were matched as well as possible on their acoustic properties, there was only one consistent difference between labial-initial and coronal-initial sequences in the French stimuli that was worthwhile pursuing: The vowel length of vowels following /p/ is always shorter compared to and vowels following /t/. With 27 ms, this difference is especially large for the vowel context /i/. This difference was not avoidable in our natural stimuli, because all vowels after /t/ were pronounced longer than those after /p/ by our native speaker of French. This lengthening might be a property of the French stimuli that enhances an LC bias for both French and Japanese participants. This LC bias might have shown in the already LC-biased French participants, but worked against the CL bias in Japanese participants such that the effects cancelled each other out in the responses of Japanese participants. In order to test this possibility, a first control experiment, Experiment 4a, tested Japanese participants' perceptual biases with French stimuli matched on vowel length. If participants indeed showed a CL effect with this altered material, this would mean that the differential vowel length could indeed have been a reason for the previous absence of a bias in response to French stimuli. If they, on the other hand, showed comparable effects to Experiment 2, we could conclude, at least for vowel lengthening, that acoustic differences in the labial and coronal sequences didn't affect the results, and that the reason had to be found elsewhere.

Another possible reason for the difference in results is that listeners indeed process native and non-native language stimuli differently, applying their perceptual biases only to the former. In order to pursue this possibility, a first important question to ask is in how far participants can tell native stimuli apart from non-native ones, which was assessed in Experiment 4b.

A second important question to ask, then, is on which level of representation the respective perceptual biases occur. If they were phonological in nature, one would assume that they generalize over a change of language. However, this would not be the case if they had difficulties mapping non-native phonemes onto their native categories. A last experiment, Experiment 4c, therefore assessed in how far Japanese adults were mapping French vowel categories onto native ones. In order to dissociate the effects of non-native language and speaker identity, recordings of a third speaker were added to the task. In order to simultaneously assess the influence of dialectal variation, we chose a native speaker of Japanese from the Ishikawa prefecture, a region that does not speak Standard Japanese. If participants had difficulties mapping French phonemes onto native language categories, but not onto dialect categories, this would give some indication of why listeners might not have processed foreign stimuli in the same way as native ones.

6. Experiment 4

Experiment 4 was designed to take a closer look at the language of presentation effects found in both experiments. Experiment 4a assessed the influence of idiosyncratic stimulus properties, Experiment 4b the extent to which participants can tell apart native and non-native stimuli, and Experiment 4c the extent to which they can map foreign vowel categories onto native ones.

6.1 Experiment 4a

The length of all vowels following /t/ was longer compared to the length of vowels following /p/ in the French stimuli, and this might have accounted for the difference in results for French and Japanese stimuli in Experiment 2: if this length difference had previously counteracted Japanese participants' CL bias, then correcting for this factor should eliminate this effect, and a CL bias should thus show.

6.1.1 Participants

Sixteen students (6 females) of several universities in Tokyo (mean age: 20.6 years; range: 18-29) with no speaking or hearing problems participated in the experiment for payment. They were all native speakers of Japanese.

6.2 Stimuli

The stimuli consisted of modified versions of the French stimuli from Experiment 2 and 3, in which the length of vowels following /t/ had always been longer than of vowels following /p/. Note that /t/s were also systematically longer than /p/s, but this was also the case for Japanese stimuli and therefore not considered a relevant factor differentiating between the French and Japanese stimuli (cf. Table 4). In order to match vowel durations, the vowel length of the vowel following /t/ was shortened to match the length of the vowel following /p/ pairwise for each vowel context /i,e,u/. Vowels were shortened by removing a part from the stable middle section of each vowel. Resulting vowel lengths are given in Table 5.

Table 5. Length of original and shortened vowels. Vowels after /t/ were shortened in order to match length of the vowel after /p/, by removing a part from the stable middle section of each vowel.

		/pe/	/te/	/pi/	/ti/	/pu/	/tu/
Duration *(ms)*	Consonant	130	145	148	170	144	153
	Vowel old	143	*158*	133	*160*	148	*156*
	Vowel new		140		133		147

6.3 Procedure

The procedure was the same as in Experiment 2. Instead of 12 trials (6 French, 6 Japanese), participants only were presented with 6 trials (French).

6.4 Results and Discussion

The overall time of perceiving the sequence as either LC or CL was 75%. A repeated-measures ANOVA with the within-subject factors Sequence and Vowel revealed no significant main effect for sequence [F(1, 15) = 0.182, p =. 676, η^2_p = .012; stability of CL sequences: M = 0.59, SD = 0.16; stability of LC sequences: M = 0.62, SD = 0.20], a marginally significant effect of vowel [F(2, 30) = 3,003, p =. 065, η^2_p = .167; /e/: M = 0.58, SD = 0.19; /u/: M = 0.69, SD = 0.20; /i/: M = 0.56, SD = 0.12], and no interaction effect [F(2, 30) = 1.119, p = .340, η^2_p = .069]. A follow-up on the marginal vowel effect revealed no significant differences between any of the three possible pairings of vowels.

The manipulation of vowel length thus did not affect the perceptual bias in Japanese participants, who still show no bias when presented with the French stimuli. Therefore, we can conclude that this idiosyncratic factor was not the reason for the absence of a CL effect for non-native stimuli in Japanese participants. Given that there was no comparable difference in /p/-initial and /t/-initial sequences in the Japanese material that could be manipulated and tested on French participants, and given that even showing an influence of such a difference on the responses of French participants would not add up to a complete picture in the face of an absence of such effects for Japanese participants, we turn to explore the second possibility, processing differences for native and foreign language stimuli, in the remainder.

6.2 Experiment 4b

A precondition for a difference in processing of native and non-native stimuli is an explicit or implicit recognition of native and non-native stimuli as such. In order to test explicit identification of native and non-native stimulus material, Japanese participants were presented the CV or CVCV sequences that constituted the original stimuli, and were asked to decide whether they heard a Japanese or a foreign speech sound.

6.2.1 Participants

Participants were the same as in Experiment 4a. Experiment 4a was always preceding Experiment 4b.

6.2.2 Stimuli

Stimuli consisted of the CV or CVCV sequences constituting the original stimuli. In the first block, CV sequences, for instance /pe/, were presented, and in the second block, CVCV sequences, for instance /pete/, were presented. Each of the 12 CV and CVCV sequences that were used in Experiment 2 and 3 were presented once to each participant.

6.2.3 Procedure

Participants were individually seated in front of a laptop computer in a sound-attenuated room and presented the experimental stimuli binaurally via a pair of headphones. Preceding the first block, they were explained that they were going to hear speech sounds of the length of one kana symbol, and were instructed to respond by button press with the index finger of the right hand if it was a ‘Japanese’, and the index finger of the left hand if it was a ‘foreign language’ speech sound. Preceding the second block, instructions informed them that they would now hear sequences of two kana symbols.

6.2.4 Results and Discussion

Participants’ mean ‘Japanese’ responses were taken as the dependent variable.

A two-way repeated measures ANOVA with the factors Language Presented (Japanese, French) and Sound Type (CV, CVCV) revealed a main effect of Language Presented [$F(1, 15) = 22.730$, $p <.001$, $\eta^2_p = .602$; 'Japanese' responses for Japanese stimuli: M = 0.55, SD = 0.15; ; 'Japanese' responses for French stimuli: M = 0.25, SD = 0.17], but no effect of Sound Type [$F(1, 15) = .302$, $p =.302$, $\eta^2_p = .020$], and no interaction [$F(1, 15) = 2.373$, $p =.144$, $\eta^2_p = .137$] (cf. Figure 4).

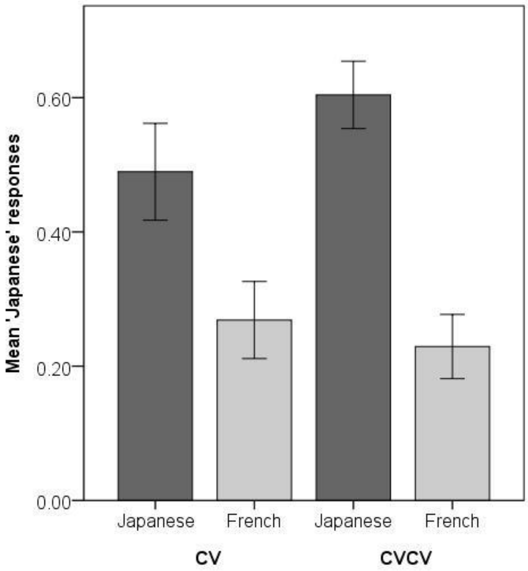

Figure 4. Mean 'Japanese' responses for the Japanese (dark grey) and French (light) grey CV (left) or CVCV (right) sequences that constituted the experimental stimuli of Experiments 2 and 3.

Japanese participants can explicitly tell apart foreign from native language stimuli, even if they only hear a CV sequence. The follow-up question, then, is what factors contribute to the absence of a perceptual bias for foreign language stimuli. We would expect a bias on phonological level to generalize to a certain degree; thus also apply to the same phoneme string uttered in a different language. However, if participants had difficulties mapping foreign phonemes onto native categories, this would be one possible explanation for the absence of a bias for non-native stimuli. In order to test this possibility, the following experiment assessed Japanese participants' discrimination accuracy of the same vowel categories in native and non-native CV sequences. In order to compare the effects of foreign language versus native language dialect, and in order to control for the effect of speaker identity, recordings from a third speaker, a native Japanese from the Ishikawa prefecture, a prefecture with a non-standard Japanese dialect, were added to the task.

6.3 Experiment 4c

Experiment 4c assessed Japanese participants’ discrimination of native vowels, non-native vowels, and native vowels produced by a speaker of non-standard Japanese. It was of interest if foreign and native vowels were more difficult to map onto each other than foreign-foreign or native-native vowel pairs disregardless of dialect, and if the foreign language effect was stronger than the effect of speaker identity.

6.3.1 Participants

Participants were the same as in Experiment 4a and 4b. Experiment 4a, 4b and 4c were always presented in this order.

6.3.2 Stimuli

Stimuli consisted of pairs of CV sequences. The CV sequences were either those constituting the stimuli of Experiment 2 and 3, or sequences recorded from a third speaker, a native Japanese from the Ishikawa prefecture. Target stimulus pairs always consisted of CV sequences with the same vowel context (cf. Table 6). For same speakers, only one pair per vowel context was used, because the same consonant pairing implied the same token. For different speaker, there were two possible combinations for the same (i.e., /pe/$_{J1}$ - /pe/$_{F1}$, /te/$_{J1}$ - /te/$_{F1}$), and two for the different (i.e., /pe/$_{J1}$ - /te/$_{F1}$, /te/$_{J1}$ - /pe/$_{F1}$) consonant context. This results in a total of 15 target tokens per participants. In addition, combinations of different vowel context, different consonant contexts and different speakers were added to the discrimination task in order to make the task more difficult. A total of 99 tokens were tested for each participant.

Table 6. Combinations of target CV sequences, examples and mean accuracy scores. J1=Japanese speaker 1, F=French speaker, J2=Japanese speaker 2 (additional speaker).

Speaker		Consonant	Example	Mean (SD)
Same	J1/J1	Same	-	0.92 (0.15)
		Different	/pe/$_{J1}$ - /te/$_{J1}$	
	F/F	Same	-	0.96 (0.11)
		Different	/pi/$_{F1}$ - /ti/$_{F1}$	
	J2/J2	Same	-	0.88 (0.21)
		Different	/pu/$_{J2}$ - /tu/$_{J2}$	
Different	J1/F	Same	/pe/$_{J1}$ - /pe/$_{F1}$	0.67 (0.21)
		Different	/te/$_{J1}$ - /pe/$_{F1}$	
	J1/J2	Same	/pi/$_{J1}$ - /pi/$_{J2}$	0.86 (0.13)
		Different	/ti/$_{J1}$ - /pi/$_{J2}$	
	J2/F	Same	/pu/$_{J2}$ - /pu/$_{F1}$	0.74 (0.18)
		Different	/tu/$_{J2}$ - /pu/$_{F1}$	

6.3.3 Procedure

Participants were individually seated in front of a laptop computer in a sound-attenuated room and presented the experimental stimuli binaurally via a pair of headphones. Upon button press, they were presented two CV sequences separated by an 800 ms silence. They were instructed to decide if the two speech sounds contained the same or different vowels and to press according buttons with the index fingers of their right and left hands. They were instructed to respond as fast and accurately as possible. A new trial started upon their response.

6.3.4 Results and Discussion

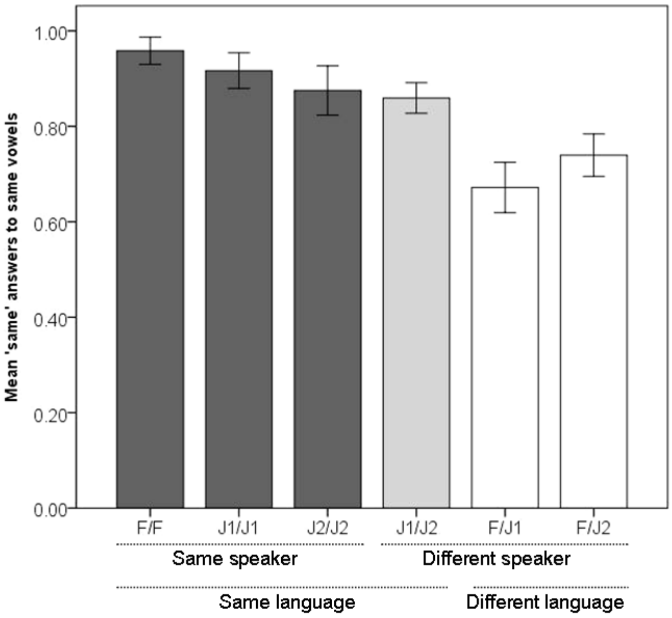

Figure 5. Mean 'same' responses to same vowel categories for same speakers (French=F/F; Japanese1=J1/J1; Japanese2=J2/J2; dark grey), different speakers-same language (Japanese1-Japanese2=J1/J2; light grey), and speakers from different languages (French-Japanese1=F/J1; French-Japanese2=F/J2).

A nested ANOVA with the main factor Speaker Identity (same, different) and the nested factor Speaker Combination was conducted. The nested factor included F/F, J1/J1, J2/J2 for the 'same' identity, and F/J1, F/J2, J1/J2 for the 'different' identity condition. A marginally significant main effect of Speaker Identity [$F(1, 4) = 7.119$, $p = .056$, $\eta^2_p = .640$; discrimination accuracy for 'same' speaker: $M = 0.92$, $SD = 0.16$; discrimination accuracy for 'different' speaker: $M = 0.76$, $SD = 0.19$], and a significant effect of the nested factor [$F(4, 90) = 3.045$, $p = .021$, $\eta^2_p = .119$] were found (cf.

Figure 5).

Bonferroni-corrected post-hoc tests at a significance level of p=.0167 revealed a significant effect only within the 'different' speaker factor, with significant differences between the accuracy for F/J1 and J1/J2 [t(30) = 3.053, p = .005] marginally significant differences between F/J2 and J1/J2 [t(30) = 2.192, p = .036], but not between F/J1 and F/J2 [t(30) = -.987, p = .332] (cf. Table 6).

These results show us that the mapping of vowels was more difficult for different speakers than for the same speaker, and that this difficulty was due to the mapping between

The effects for the same vowels show that participants had more trouble mapping the vowels by the French speaker onto Japanese categories than mapping the vowels of the respective Japanese speakers onto each other. This fits a picture in which our French stimuli were not mapped onto any Japanese native categories, and thus were possibly not processed according to native language phonology.

6. General Discussion

In the present study, we investigated the question of whether the LC bias is determined by motor factors, perceptual factors, or both. Previous studies have found evidence for both motor (Rochet-Capellan & Schwartz, 2007) and perceptual (Sato, et al., 2007) influences, the former indicating a general mechanism, and the latter a language-specific one. However, due to the fact that these studies were exclusively conducted in languages with a higher frequency of LC compared to CL sequences, they have not been able to isolate the relative influence of perceptual input on both productive and perceptual preferences.

Japanese has been claimed to be a language with the opposite bias (MacNeilage, et al., 1999), making it a candidate language for disentangling accounts. Due to the fact that this claim was based on a very small sample of words, we conducted a large-scale corpus analysis in order to reevaluate these previous findings. Across corpora and analyses, we found that the subset of plosives consistently showed a CL bias, while the subset of nasals, as well as the analysis of all segments, showed an LC bias. The deviation of our current findings from the previous ones is possibly due to the small sample size, as well as the very selective vocabulary covered in the travel dictionary used in the previous study. Finding an overall LC bias in the only language that has been claimed to favor the opposite pattern to date leads further support to the notion that the LC bias is predominant in languages of the world (MacNeilage & Davis, 2000). Importantly, however, despite the overall LC bias, the subset of plosives did show a CL bias. Plosives are among the first segments children produce (cf. MacNeilage, et al., 2000), which makes an investigation of this subset of special interest to early speech development: The LC bias in early production reported by MacNeilage et al. (2000) concerns plosives and nasals in English, a language that also an LC bias in the input. Looking at early productions in Japanese, in which plosives have the opposite bias, will contribute to understanding in how far the early LC bias really is a universal bias as opposed to an input effect.

Having singled out a subset of segments with a consistent CL bias in Japanese, we investigated the productive preferences of Japanese adults with regard to plosive LC and CL sequences. In the context of a speeded articulation task, Japanese participants, like French adults (Rochet-Capellan & Schwartz, 2007), showed a tendency to reduce LC and CL CVCV clusters into LC CCV clusters. This suggests that LC plosive sequences are articulatory more stable for speakers of Japanese despite the higher frequency of CL plosive sequences in their input, and provides strong support for an account that bases the higher prevalence of LC patterns in languages of the world on characteristics of the human motor system. Further, this result seems remarkable in the light of Japanese phonotactics, in which CCV consonant clusters are illegal. However, Tokyo Japanese entails phonological devoicing after the vowels /u/ and /i/, which in fact regularly leads to the production of consonant clusters (e.g., “tsukuru” → “ts’kuru”). Moreover, work on the perception of CCV clusters (Dupoux) has shown that Japanese listeners, when presented with consonant clusters perceive epenthetic vowels (e.g., /ebzo/ is perceived as /ebuzo/), illustrating that they have a repair mechanism for devoiced forms to fit into native phonology. Thus, our data might be a nice illustration of the fact that the production system is capable of producing CCV clusters, and even inclined to do so if it benefits articulatory ease, while the perception system provided a mechanism to fit ill-formed sequences into native language phonology.

Contrary to the results in production, Japanese listeners showed a language-specific bias in online speech perception and preferred CL over LC plosive sequences. These findings are in line with numerous studies showing an influence of native language phonology on segmentation (e.g., McQueen, 1998; Mersad & Nazzi, 2011; Peña, et al., 2002; Saffran, et al., 1996; Weber & Cutler, 2006). They are also consistent with the developmental finding that French infants start out without any bias at 6 months of age, but develop an LC bias by 10 months (Nazzi, et al., 2009; Gonzalez-Gomez & Nazzi, 2012), which is in line with other studies of infant speech perception (e.g., Friederici & Wessels, 1993; Jusczyk, et al., 1993; Jusczyk, et al., 1994). The finding that Japanese listeners show a perceptual CL bias despite the fact that their overall input (i.e., considering all manners of articulation) is biased towards LC also suggests that this perceptual bias applies at the level of manner of articulation rather than overall. These results complement recent findings with French adults (Sato, et al., 2007) and infants (Gonzalez-Gomez & Nazzi, 2012; in preparation). French has an LC bias both overall and for the subgroup of plosives; however, the subgroup of fricatives shows a CL bias. Gonzales Gomez & Nazzi find that 10-month-olds' perceptual bias for different manners of articulation is directly related to the input bias in the respective manner, i.e. LC for plosives, but CL for fricatives. Further, voiced plosives have a CL bias, but nevertheless French adults show an LC bias to this subgroup (Sato, et al., 2007). These findings in combination with the results of the present study suggest a picture of the perceptual LC and CL bias applies at the level of manner of articulation. Further studies are needed to clarify if Japanese listeners indeed show a perceptual LC bias if presented with stimuli in other manners of articulation. Due to the lack of sufficient labial segments in fricatives, this study would have to be conducted on nasals.

Both Japanese and French participants show an influence of the language presented. Japanese listeners exhibited a CL bias for the Japanese stimuli only, while French listeners in turn showed an LC bias exclusively for the French stimuli. Thus, both groups of listeners do not show a statistically significant bias when listening to their non-native language, indicating that this language-specific sequential bias is likely not generalized to instances in other languages. In a series of control experiments, we showed that a salient idiosyncratic difference in French stimuli, a difference in vowel length for vowels after /t/ and /p/, did not change the absence of the bias with non-native stimuli. We further showed that Japanese participants do explicitly distinguish between native and foreign stimuli, and that they have trouble mapping French stimuli onto native language categories. Thus, our evidence suggests that the low familiarity of the vowel categories of the non-native language is a possible reason for this outcome. Differences in the phonetic properties of plosives might also contribute to the absence of a bias in the non-native language.

Plosives in French are mostly unaspirated (Fougeron & Smith, 1993), while plosives in Japanese can be weakly aspirated (Okada, 1991), with voice onset time (VOT) of Japanese voiceless stops falling between average VOTs for unaspirated and aspirated stops in other languages (Riney, Takagi, Ota, & Uchida, 2007).

The above findings are difficult to reconcile with a perception-action link in determining the LC bias. In their study of the relation between speeded production and verbal transformations, Sato et al. (2007) found support for the notion of a perception-action link in the LC bias, suggesting that this link plays a role in the case of the perceptual LC bias in French. The results of the current study do not exclude this possibility for French; however, the observed dissociation between perception and action for Japanese suggests that, if such a perception-action link is present, other factors can override it. In other words, the Japanese data suggest that, when there is a CL bias in the input, it wins over the production constraint for an LC bias.

Remaining questions are, firstly, how prevalent the LC bias actually is in languages of the world, and where the plosive CL bias in Japanese originates. Although the corpora examined by MacNeilage at al. (1999) cover several language families, they are far from complete. Historically, Japanese has borrowed heavily from the Chinese language in both script and sound, and although controversial, some roots in the Korean language are also assumed (Lee & Hasegawa, 2011). Starting out with languages that are close to Japanese, further languages have to be examined in order to get a better picture of the pervasiveness of the LC bias across languages of the world.

Secondly, adult listeners' biases for different subclasses of consonants in different languages are of interest. Both our results and Gonzalez-Gomez and Nazzi (in preparation) suggest that listeners develop input-specific biases at the level of manner of articulation. Exploring further subclasses of consonants in different languages with different predictions for different manners of articulation will be necessary in order to confirm this tendency.

Thirdly, in light of the adult findings, it is of interest to evaluate what we can expect with regard to infants' developing production and perception. With regard to perception, both the findings of the current study and the findings with French infants allow the prediction that Japanese infants will show an input bias, i.e. a CL bias for plosives and LC bias otherwise. With regard to infants' early productions, if we assume that articulatory stability plays a major role, we can expect an LC bias as found in Japanese adults. However, other factors might influence early productions, especially early words. MacNeilage and Davis (2000) found an LC bias in infants' first words, but not yet in babbling. As infants have been exposed to their native language's input for quite some time by the time they start producing words, an influence of input frequency cannot be excluded based on these data. Direct support for such an influence on the development of an LC bias in production comes from Fikkert & Levelt (2002), who report a correlation between the time-point children produce CVC sequences of a given place of articulation structure with the frequency of these structures in child-directed speech. In their longitudinal study, the high frequency of LC words produced by Dutch children in a certain stage is reflected in the high frequency of words with LC structures in their child-directed input. Although Japanese has an overall LC bias, plosives, the segment group that is among the first to be produced by infants, present a CL bias. Production data of Japanese infants and young children would therefore be a strong test of a hypothesis that assumes infants to start out with an LC bias in early production. If this were indeed found, a further step would require longitudinal data of Japanese children's productions, as learners of Japanese have to shift to a higher production rate of CL sequences eventually in order to get close to adult distributions.

7. Conclusions

Overall, our data support the notion that the productive LC bias is rooted in properties of the human articulatory system. However, perceptual preferences of these same sequences are influenced by distributional frequencies of the native language. There is no necessary perception-action link in the labial-coronal bias, and further language inventories have to be studied in order to get a more complete picture of the pervasiveness of these biases.

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